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AN INDEPENDENT COMPARISON OF PLANNED DESIGN PERFORMANCE AND THE OBSERVED PERFORMANCE OF THE NORTH BOUNDARY PILOT CONTAINMENT SYSTEM. SPECIFIC TASKS INCLUDED IN THE PROGRAM FOLLOW: 1) REVIEW DESIGN PERFORMANCE PREDICTIONS OF THE DEWATERING AND RECHARGE WELL SUBSYSTEMS AND WATER LEVEL FLUCTUATIONS OF THE SURROUNDING MONITORING WELLS, 2) REVIEW ACTUAL PERFORMANCE DATA OF THE DEWATERING AND RECHARGE WELL SUBSYSTEMS AND WATER LEVEL FLUCTUATIONS FOR THE SURROUNDING MONITORING WELLS, 3) COMPARE ACTUAL AND PREDICTED PERFORMANCE DATA, AND 4) PROVIDE EXPLANATIONS FOR OBSERVED DIFFERENCES, AS APPROPRIATE, BETWEEN ACTUAL AND PREDICTED PILOT CONTAINMENT SYSTEM PERFORMANCE. FOR THIS COMPARISON, ONLY THE EFFECT OF THE NORTH BOUNDARY PILOT CONTAINMENT SYSTEM ON (A) THE ALLUVIAL AQUIFER SYSTEM VICINITY AND (B) THE REMOVAL OF THE CONTAMINANTS DIMP AND DCPD FROM THE GROUNDWATER SYSTEM ARE CONSIDERED.

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Report

Evaluation of North Boundary Pilot Containment System

B7900055

D'APPOLONIA

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EVALUATION OF ROCKY MOUNTAIN ARSENAL NORTH BOUNDARY PILOT CONTAINMENT SYSTEM

1.0 INTRODUCTION

The Rocky Mountain Arsenal (RMA) is located approximately 10 miles northeast of the central business district of Denver, Colorado and immediately north of the Stapleton International Airport (Figure 1). This facility has been utilized for manufacture or detoxification of various organic chemicals since the early 1940's. Industrial wastes generated by these operations have been discharged to several waste basins located south of the pilot containment system (Figure 1). The first reported indication of groundwater contamination associated with RMA activities was in 1954 when several farmers north of the arsenal complained of damage to crops irrigated with water pumped from the alluvial aquifer (Kolmer and Anderson, 1977b). A new disposal basin with a low permeability liner (Reservoir "F") was completed in 1957 for the purpose of alleviating the contamination problem. In 1974, diisopropylmethylphosphonate (DIMP) and disyclopenladine (DCPD) were found to be present in waters discharging from a bog located along the north boundary of the RMA. DIMP was also detected in water supply wells for the city of Brighton in December of 1974. The off-post detection of DIMP and DCPD prompted the Colorado Department of Health to issue three Cease and Desist Orders on April 7, 1975 that required an immediate stop to the surface and subsurface discharge of DIMP and DCPD, development of a plan to preclude future discharge of the contaminants, and development of a monitoring program to verify compliance with the orders.

From 1975 to 1977, several investigators were involved in hydrologic investigations and the design of a contaminant containment and treatment system for a portion of the northern boundary of the RMA. These studies and reviews were conducted by Konikow (1975), Reynolds (1975), Miller (1977), Mitchell (1976), Kolmer and Anderson (1977a and b), Thomas, et al., (1977), and Robson (1977). The studies resulted in the installation of the present pilot containment system along a portion of the northern RMA boundary (Figure 1).

D'Appolonia Consulting Engineers, Inc., (D'Appolonia) was retained by Battelle Columbus Laboratories under Scientific Services Agreement Delivery Order No. 1245 to provide an independent comparison of planned design performance and the observed performance of the north boundary pilot containment system. Specific tasks included in the program follow:

- Review design performance predictions of the dewatering and recharge well subsystems and water level fluctuations of the surrounding monitoring wells.
- Review actual performance data of the dewatering and recharge well subsystems and water level fluctuations of the surrounding monitoring wells.
- Compare actual and predicted performance data.
- Provide explanations for observed differences, as appropriate, between actual and predicted pilot containment system performance.

For this comparison, only the effect of the north boundary pilot containment system on (a) the alluvial aquifer system in the vicinity and (b) the removal of the contaminants DIMP and DCPD from the groundwater system are considered. The sources of information used in this evaluation are identified in the attached bibliography.

2.0 DESCRIPTION OF NORTH BOUNDARY PILOT CONTAINMENT SYSTEM

A pilot containment system was designed and installed along the north boundary of the Arsenal to demonstrate compliance with the Cease and Desist Orders. The pilot containment system, as implemented, consists of the following elements:

- Dewatering wells subsystem
- Treatment plant
- Recharge wells subsystem
- Impermeable barrier
- Monitoring subsystem

A flow schematic and plan layout of these elements are shown in Figures 2 and 3, respectively. The location of monitoring points relative to the north boundary pilot containment system and surface topography are shown in Figure 4. The operation of the north boundary pilot containment system began on July 25, 1978. Data from monitoring wells in the north boundary area are available prior to the startup.

The operation of the pilot containment system relies on an impermeable groundwater barrier to stop the flow of contaminated water. Dewatering wells on the upgradient side of the barrier remove water from the aquifer for treatment while recharge wells on the downgradient side of the barrier inject the treated water back into the aquifer. Brief descriptions of each of the subsystems follow:

- Dewatering Well Subsystem - This system consists of six 8-inch diameter wells installed within 30-inch diameter gravel packed holes. The wells are approximately 230 feet apart, and are screened through the full thickness of the alluvial aquifer. Each well has a submersible pump and flow control system. The pumping system is designed to maintain a constant head within each well. This is accomplished by means of a level sensing probe controlling a motorized valve at the wellhead that will cause the water pumped to be recycled back into the well when the pumping level drops below the cutoff probe (personal communication with John Wardell).

- Treatment Plant Subsystem - A schematic flow diagram illustrating components of the treatment plant subsystem is presented in Figure 2. The contaminated dewatering well effluent is discharged to a sump from which it is pumped through a dual media filter to remove suspended solids. The filtered water is then circulated through two activated granular carbon columns. DIMP and DCPD are adsorbed by the activated carbon and the treated effluent is then discharged by gravity drainage to the recharge well subsystem. The current design capacity of the treatment plant is 10,000 gallons per hour (Kolmer and Anderson, 1977b).

- Recharging Well Subsystem - The recharge well subsystem consists of twelve 18-inch diameter, wells installed within 36-inch diameter gravel packed holes. The wells are typically spaced at about ± 115 feet. These wells are also screened the full thickness of the aquifer. The water level is maintained below a maximum level by a float control valve. If the water level in the recharge well rises above the preset maximum level then no water is discharged to that well.

- Impermeable Barrier - This component of the system is a bentonite slurry wall separating the dewatering well line from recharging well line. The function of this wall is to physically cut off the natural movement of groundwater through the aquifer for the purpose of isolating the upgradient and downgradient flow. In the completed containment system, this barrier will preclude mixing of potentially contaminated and treated waters.

- Monitoring Wells - The monitoring wells are a series of observation holes distributed both upgradient and downgradient of the pilot containment system (Figure 4). These observation wells are completed with small diameter PVC casing screened within the alluvial aquifer. Water levels and chemical quality of the groundwater are monitored periodically at various of these wells.

3.0 SITE HYDROGEOLOGY

3.1 AQUIFER DESCRIPTION

In and around the north boundary pilot containment system, the aquifer of concern is composed of unconsolidated well-sorted sands and sandy gravels. The well-sorted sand unit comprises the majority of the productive aquifer thickness. This unconsolidated aquifer is in contact with low permeability claystone bedrock of the Denver Formation. Due to the great difference in permeability between the consolidated claystones and the sand and gravel aquifer, the bedrock is assumed to act as an impermeable lateral and lower boundary. Overlying the productive aquifer units are silty sands and clays. The depth to the top of the alluvial aquifer is typically less than 15 feet. The alluvial aquifer has a cross-sectional width of approximately 5,000 feet in the vicinity of the northern boundary of the RMA. The eastern and western aquifer boundaries are formed by thinning of alluvial deposits over bedrock highs.

The plan view of the locations where the bedrock highs cause a thinning of the alluvial deposits are identified in Figure 4 as aquifer boundaries; these are approximate and based on the available data. A diagramatic geologic cross-section along a portion of the north boundary of the RMA is presented in Figure 5. The alluvial deposits fill an ancient valley cut into the bedrock. Typically, the alluvial aquifer is thicker near the eastern aquifer boundary where the maximum saturated thickness of about 15 feet occurs. The aquifer thins to about 3 feet near the western bedrock high, where the pilot containment system has been located.

Recharge to the aquifer is by infiltration of rainwater and snowmelt and possibly by leakage of the various surface impoundments located on the Arsenal grounds. The average annual precipitation is 15.5 inches per year (Kolmer and Anderson, 1977b). The potentiometric surface of the aquifer is lowered during the summer growing season (when evapotranspiration is high) and rises in the fall, winter, and spring. The magnitude of the seasonal fluctuation is as much as 2.5 feet (Mitchell, 1976).

3.2 GROUNDWATER HYDROLOGY

Groundwater in the alluvial aquifer occurs under both confined (potentiometric level above the top of the aquifer) and unconfined conditions (potentiometric level below the top of the aquifer) depending on the specific location. For example, along the northern RMA boundary, the aquifer is confined along the eastern end and unconfined along the western end near the pilot containment system. Whether the aquifer is confined or unconfined is also dependent on the time of year because the water levels rise or fall in response to recharge. The preoperational potentiometric surface map is provided in Figure 6. This map was developed using potentiometric level information for the months of February and March 1978. The gradient on the potentiometric surface ranges from 0.0067 to 0.0086 trending toward the north in the vicinity of the north arsenal boundary. Where data is available, the potentiometric contours coincide approximately with the potentiometric maps developed by Robson (1976).

Aquifer tests have been conducted at numerous locations in the vicinity of the northern RMA boundary in both 1976 and 1978 by the Corps of Engineers, Waterways Experiment Station (WES). The work completed in 1976 (Mitchell, 1976) included formal aquifer tests at three locations along the northern RMA boundary. Each of these test wells had a battery of piezometers installed at various distances for water level measurements during the test pumping. The results of this initial testing program estimated permeabilities in the alluvial aquifer to be about 1,500 gpd/ft^2 (200 ft/day). The results of this testing program demonstrated considerable variability due to the widely fluctuating pumping rates during the tests. Subsequent reanalysis of the data from this test was completed by Battelle-Moody (Thomas, et. al., 1977) and their analysis was in substantial agreement with the WES results. In addition, a storage coefficient of 0.05 was estimated during this reanalysis (Thomas, et al., 1977). These analyses were used for design and development of performance projections for the pilot containment system.

In 1978, five additional aquifer tests were conducted by WES at various locations in the alluvial aquifer south of the north boundary pilot containment system (Vispi, 1978). These tests were conducted for a considerably greater length of time than those conducted in 1976 and constant discharge rates were maintained for the duration of each of the tests. These two factors resulted in a more reliable estimate of the alluvial aquifer characteristics. The range in permeabilities found during this second testing program was from 793 gpd/ft^2 (106 ft/day) to 9,690 gpd/ft^2 (1,295 ft/day). In the vicinity of the north boundary pilot containment system, the tests indicated permeability in the range of 3000 gpd/ft^2 (400 ft/day). Results of testing at Borehole No. 345 near the eastern side of the northern RMA boundary (Figure 4) were selected as representative of alluvial aquifer characteristics. The testing at this location yielded a permeability estimate of approximately 3000 gpd/ft^2 (400 ft/day).

The transmissivity calculated by Vispi (1978) for this pump test was used in this investigation to estimate permeabilities for sand and sand and gravel units in the alluvial aquifer. The permeability contrast between the sand and gravel unit and the sand unit was estimated by D'Appolonia to be 60 percent, i.e., sand permeability is 60 percent of sand and gravel permeability. When the respective sand unit and sand and gravel unit (relatively thin at this location) thicknesses at Borehole No. 345 were used in conjunction with the estimated permeability ratio, permeabilities of about 3,000 gpd/ft^2 (400 ft/day) for the sand and about 5,000 gpd/ft^2 (668 ft/day) for the sand and gravel unit were calculated.

In order to estimate an approximate flow across the width of the alluvium along the northern RMA boundary, saturated aquifer unit thicknesses from boring logs and the permeability information defined above were utilized. At selected locations, where borehole information is present, the transmissivity for a one-foot wide section of saturated aquifer (both the sand unit and sand and gravel unit) was calculated using the following equation:

$$T_{total} = T_{sand} + T_{sand\ and\ gravel} \qquad (1)$$

T is the transmissivity and is determined by:

$$T = K \cdot m \tag{2}$$

where:

K = permeability ($K_{sand} \approx 3000$ gpd/ft^2 and

$K_{sand\ and\ gravel} \approx 5000$ gpd/ft^2)

m = saturated thickness of aquifer unit (determined from the borehole log using average water levels)

This is an approximation due to use of average saturated thickness. The transmissivity for the total thickness of saturated aquifer at various borehole locations is plotted in Figure 7.

In order to establish a flow rate at each of the specific locations, the following equation is used:

$$Q = T \cdot i \tag{3}$$

where:

Q = flow rate (gpd) for a one-foot width

T = Transmissivity (gpd/ft)

i = Gradient (feet per foot)

Kolmer and Anderson (1977b) measured a gradient (i) of 0.0067 ft/ft. Using the information presented in Figure 6 (data base February and March, 1978), a gradient of about 0.0086 ft/ft was measured for this investigation. A flow rate was calculated at specific borehole locations using both gradient values. The results of these calculations are presented in Figure 7. In order to obtain the total flow across the northern RMA boundary, the area under the flow rate curve (Figure 7) was calculated. For a gradient of 0.0067 ft/ft, the total flow was calculated to be approximately 43,000 gallons per hour (gph) and for the gradient of 0.0086 ft/ft the total flow was approximately 55,000 gph.

The velocity of the groundwater flow varies with the permeability and gradient changes across the northern RMA boundary. Using the estimated average permeability of 400 ft/day and an average gradient of 0.0086 ft/ft, the Darcian velocity of 3.44 ft^3/ft^2 day is estimated. By dividing this value by an estimated effective porosity of 30 percent (Lambe and Whitman, 1969), an actual pore velocity of 11.5 ft/day is estimated under the natural gradient for the February to March, 1978 period.

3.3 PREOPERATIONAL DISTRIBUTION OF SELECTED CHEMICAL PARAMETERS

The contaminant concentration maps presented in this report were prepared using data provided by RMA (1977, 1978, and 1979). For selected periods, concentration data was plotted for various contaminants. This information was then contoured using linear interpolation between known data points. Variance to the linear interpolation procedure occurred in only a few localized instances, where a temporal comparison with other maps of the same contaminant suggested a more realistic contour location. It is acknowledged that groundwater dispersion of chemical species is not expected to be a linear function and that the contours presented could change if substantially more data were gathered. However, for the purposes of a graphical display of gross temporal changes in the groundwater chemistry, the above described method of contouring is consistent, useful, and adequate.

The contaminant DIMP was present throughout the alluvial aquifer in the north boundary area. Reported DIMP concentrations from the period June through December, 1977, and June and July, 1978 were plotted and contoured in Figure 8. Considering the mixture of data, Figure 8 provides a very approximate graphical description of the presystem distribution of DIMP. The highest detected concentrations occurred at Monitor Wells 313 [10,600 micrograms per liter (μg/ℓ)], 47 (3514 μg/ℓ), and 13 (3360 μg/ℓ). Concentrations were relatively low (<500 μg/ℓ) in the vicinity of Monitor Wells 306 (136 μg/ℓ), 8-Section 23 (21 μg/ℓ), 11 (11 μg/ℓ), 10 (μg/ℓ), 2 (71 μg/ℓ), 8-Section 24 (483 μg/ℓ), and 9 (364 μg/ℓ).

A DCPD concentration map (Figure 9) to describe approximate presystem conditions was prepared in a similar manner. The majority of the area showed relatively low concentrations (260 μg/ℓ or less). However, in the vicinity of the intersection of Tenth Avenue and Peoria Street preoperational concentrations as high as 2290 μg/ℓ were measured (Monitor Well 43). Work by Mitchell (1976) identified a definite plume of DCPD concentration extending downgradient from Reservoir "F". The available data for 1977 and 1978 do not confirm the presence of this plume.

A presystem chloride concentration map was also developed (Figure 10). Chloride concentrations are used in this report primarily as a reference because they are typically nonreactive with the aquifer media and are not removed by the pilot plant treatment system. The presystem chloride distributions are somewhat similar in pattern to DIMP distributions. Monitor Well 313 [2240 milligrams per liter (mg/ℓ)] had a relatively high concentration. Monitor Wells 309 and 13 showed 613 mg/ℓ and 822 mg/ℓ, respectively. Other well data typically showed concentrations less than 500 mg/ℓ.

4.0 PILOT CONTAINMENT SYSTEM PERFORMANCE PREDICTIONS

4.1 BASIC ASSUMPTIONS AND PREDICTIVE MODEL

In comparing the predicted pilot system performance with actual performance, the assumptions and model used in developing the prediction were examined. The model was based on the confined equilibrium radial flow form of Darcy's equation. The form of the equilibrium equation used to predict performance in the final EIS (Kolmer and Anderson, 1977b) follows:

$$h(x,y) = \frac{1}{4\pi} \sum_{i=1}^{n} \frac{Q_i}{T_i} \ln\left[(x-x_i)^2 + (y-y_i)^2\right] + C \qquad (4)$$

where:

h = drawdown

x,y = cartesian coordinates of point for which drawdown is to be determined

Q_i = discharge rate at well i

T_i = transmissivity at well i (assumes confined conditions)

x_i, y_i = pumping well location

C = constant (function of configuration of well system, Q, T and radius of influence)

The two critical parameters in the hydrologic analysis are the permeability of the aquifer and the radius of influence of the wells. The predictions were based on permeabilities of 200 ft/day (1,500 gpd/ft^2) in the thicker portion of the aquifer on the east end of the pilot system while a permeability of 150 ft/day (1,120 gpd/ft^2) was used for the western side of the pilot containment system. The basis for the lower permeability on the western side is that the grain size of the sediments is normally finer. The estimate of radius of influence was set at 500 feet due to lack of response of observation piezometers at that distance during short term pumping tests. The Theis nonequilibrium equation was used to estimate the time it would take the radius of influence to reach the distance of 500 feet; that equation follows:

$$s = \frac{Q}{4\pi T} \int_{\frac{r^2S}{4Tt}}^{\infty} \frac{e^{-u}}{u} \, du \qquad (5)$$

where:

$u = \frac{r^2S}{4Tt}$

s = drawdown

r = distance from pumping well to observation point

S = storage coefficient

e = natural logarithm base

t = time of pumping

T = transmissivity

Q = pumping rate

(Kolmer and Anderson, 1977b)

The storage coefficient is the only additional parameter necessary for this evaluation.

The presence of the impermeable barrier was simulated by the use of image wells symmetrically located about the slurry wall. The use of image wells allows simulation of a no flow boundary at the slurry wall. The form of the nonequilibrium equation used to solve for drawdown at each well involves a summation or superposition of drawdown components from each well and each image well. The equation is as follows:

$$s = \sum_{i=i}^{i=n} \frac{Q_i}{4\pi T_i} \int_{\frac{r_i^2 S}{4T_i t}}^{\infty} \frac{e^{-u}}{u} \, du \qquad (6)$$

The definition of terms is the same as in Equation 5.

This was based on a storage coefficient of 0.03 which was determined from the 1976 testing program. The nonequilibrium equation matched the drawdowns from the equilibrium equation after seven days. When the drawdowns from these two solutions match, that signifies the transient expansion of the cone of influence reached the assumed radius of influence at the end of seven days.

Table 1 is reproduced from information presented in the final EIS and compares the predicted pumping rates and drawdowns at the seven day (calculated equilibrium) drawdown with the observed system pumping rates and drawdowns after ten days of operation. A more direct comparison is achieved by employing the actual pumping rates observed in the first ten days of system operation with the nonequilibrium predictive model of Kolmer and Anderson (1977b). The modified nonequilibrium predictions are shown in Table 2. Since the first available data on drawdown was collected at ten days after the startup, the predicted drawdown at this time was also calculated and shown in the table. The comparisons indicate that the observed drawdowns were smaller on the eastern side of the dewatering well line than were predicted (Table 2). Response at the western side is somewhat ambiguous with some wells showing greater drawdown and others less drawdown than predicted.

The discrepancy between the predicted drawdowns and the results of the 1978 aquifer testing program suggest that the predictive model should be updated. Examination of data collected since 1977 and reconsideration of the assumptions associated with the 500 feet radius of influence indicate that a greater influence radius occurs. Factors that would allow an equilibrium condition to be reached at the 7-day pumping period would include the following:

- Surface recharge
- Leakage from overlying or underlying aquifers
- Induced infiltration

None of these factors are anticipated to contribute sufficient quantities of water to the aquifer to allow equilibrium to be approached at time periods as small as seven days. The nonequilibrium equation used by Kolmer and Anderson was evaluated to estimate how far the cone of influence of the system might spread in one year of operation and the results show a radius of about 3,000 feet to be more appropriate to approximate equilibrium conditions. Supportive evidence for this larger area of influence is provided by declines in water levels for wells located over 1,000 feet from the dewatering wells. Examination of water level data near the dewatering wells also indicates that declines continued nominally for 30 to 60 days before the changes become undetectable. This is considerably in excess of the seven days predicted to reach equilibrium conditions.

Based on the comparisons and the additional data now available a new predictive model was implemented. In order to duplicate the response characteristics of the alluvial aquifer in the pilot containment system area, a well field simulator was developed. The simulator solves the Theis nonequilibrium equation for each pumping or injection well and simultaneously superimposes the solution on each of the other wells in the simulation. The barrier effects were simulated by including image wells to yield a no-flow boundary at the slurry wall barrier. This model includes corrections for decreasing saturated thickness near the wells using Glover's second approximation (Glover, 1974).

Parameter values for the simulation of dewatering well performance were estimated from results of the pumping test at Borehole No. 345 (Vispi, 1978). Permeabilities of 1,500 gpd/ft^2 (200 ft/day) were used for the two westernmost wells (320 and 321) in the dewatering line; permeabilities of approximately 3,000 gpd/ft^2 (400 ft/day) were used for the remaining wells. The lower permeability was estimated at the western edge of the pilot system due to the finer grain nature of the aquifer at that location. A storage coefficient of 0.10 was conservatively estimated for the unconsolidated sands and gravels [the value used in Theis design prediction was 0.03 (Kolmer and Anderson, 1977b)]. The value of 0.10 is considered to be representative for long-term pumping due to greater drainage of pore space over long time periods.

The responses of individual dewatering wells were used to calibrate the well field simulation model. The simulator plan view of the pumping wells and image wells are shown in Figure 11. The parameter values for the calibrated simulation are provided in Table 3. Imaginary observation wells were incorporated with the model to check the response of the aquifer at various distances from the dewatering line. The distances of these imaginary observation wells corresponds approximately to the real observation wells. Actual average pumping rates over the first 60 days of operation were simulated and the permeabilities in the model adjusted as necessary to duplicate the response of the actual system. The calculated drawdowns at 60 days are compared with observed drawdowns in Table 4. The observed drawdowns are not shown at the observation wells due to the 'noisy' nature of the data i.e., the normal water fluctuations are of a similar magnitude to the water level response to pumping. The ability to match observed-to-calculated system responses by using permeabilities of approximately 3,000 gpd/ft^2 (400 ft/day) as found by Vispi (1978) suggests that these permeabilities are realistic.

The well field simulation model has certain inherent limitations. Complex boundary effects related to both lateral changes in transmissivity and the physical barrier effects of the bedrock highs complicate the actual system. The equations used in the simulation assume a homogeneous, isotropic and infinite aquifer system. The equations used also assume no change in transmissivity as a function of drawdown. This limitation is at least partially resolved by using Glover's (1974) approximation modification of the Theis equation to correct for decreasing saturated thickness in the vicinity of a pumping well.

Another prediction of system performance made in the EIS was that the total groundwater flux across the 1,400 foot barrier alignment equalled 4,200 gallons per hours, using a gradient of 0.0067. Calculations of the groundwater flux based on these updated analyses show a 12,000 gallons per hour groundwater flux across the barrier alignment. The primary reason for the higher flow estimate is the increased permeability that has been determined to be more representative. The analysis indicates that only about 1/3 of the natural flow is being diverted through the treatment system, with the remaining flow going around the barrier. This item is further addressed in the following discussion.

5.0 EVALUATION OF SYSTEM PERFORMANCE

5.1 EFFECTS ON HYDROLOGIC SYSTEM

Operation of the pilot containment system has had a significant impact on observation wells near the containment system but, outside of the effects local to the pumping-recharge zone, there is no significant effect on the prevailing potentiometric surface. Figure 12 illustrates the areal potentiometric surface during system operations. Larger scale potentiometric surface maps showing details around the system are presented in Figure 13 and 14. The maximum drawdown has been 4.56 feet at Dewatering Well No. 320 and the maximum build-up has been 8.27 feet at Recharge Well No. 332. Away from the dewatering and recharge wells the water level changes have been less. The maximum amounts of drawdown or build-up for any given well are difficult to determine because detailed preoperational data is not available for the wells close to the dewatering and recharge wells. The natural water level fluctuations tend to obscure the changes at wells further from the plant (over 250 feet). Relative drawdown and build-up values have been derived from interpreting preoperational trends of the water levels for those wells in the estimated radius of influence (less than 3,000 feet from the dewatering wells) and comparing these trends with wells over 3,000 feet from the dewatering wells. Analyses of water level trends indicate that declines of less than one foot have occurred for wells located over 1,000 feet from the dewatering wells. On the recharge side, water level build-ups have typically been less than two feet for wells located within 200 feet of the recharge wells.

The amount of water diverted from the flow system through the plant has averaged 3,000 gallons per hour and the estimated natural flow through this section of the northern boundary is approximately 12,000 gallons per hour. Examination of the potentiometric maps around the pilot containment system (Figures 13 and 14) indicates that the excess flow is being diverted around the barrier. This indication is based on deflection of contour lines.

In addition to a change in orientation of flow vectors in the vicinity of the slurry wall, a localized change in gradient is indicated. This change in gradient is based on a comparison of the contours in the vicinity of the slurry wall and area away from the wall. An increase in water levels would be expected at monitoring wells around the margin of the barrier if flow is taking place around the barrier. No preoperational data is available in these areas to confirm this hypothesis. The rise in water level necessary to accommodate the increased flow around the barrier amounts to only a few tenths of a foot; such a small increase cannot be distinguished from other influences.

Regionally, the natural water level gradients have not changed appreciably due to system operation with the gradient across the northern arsenal boundary being between 0.006 and 0.0125 both before and after system installation (Thomas, et al., 1977). In comparing water level trends for the wells in the area of the plant with those over 3,500 feet away, it is concluded that the pilot plant does not influence regional gradient changes.

5.2 TREATMENT PLANT EFFECTIVENESS

Chemical quality of the filter effluent and the adsorber (activated carbon column) effluent is monitored within the plant at close intervals. Comparison of the chemical analysis of the filter effluent with the adsorber effluent indicates that only organic compounds are removed by the adsorber and the inorganic compounds remain unchanged. DIMP and DCPD are the major constituents of the organic fraction. Other organic compounds are also indicated in the analysis to be present as minor but consistent constituents of the filter effluent.

Using the flow rate data for dewatering wells and daily organic chemical concentration data, the cumulative recovery rates for DIMP and DCPD were calculated. Figure 15 is the plot of cumulative weight recovered by the plant versus time. During an eight month operation of the plant for which data was available, about 73 kilograms of DIMP and 67 kilograms of DCPD were recovered.

Changes in the slopes of these graphs could be indicative of any or all of the following factors:

- Variation of flow through the plant.
- Variation in the concentration of a given constituent in the inflow.
- Failure of the adsorber.

Adsorber failure for DIMP recovery occurred once during November and December 1978, as evidenced by slight flattening of the DIMP recovery graph. As can be seen in the flow histogram, the flow rate was increased in late August 1978. The steepening of the slope of the DIMP graph is evidently the result of the flow increase. The increase in the slope of the DCPD graph that occurred in early September 1978 is attributed to a change in the inflow concentration of DCPD, as no changes in the flow rate or plant removal function occurred at this time.

If flow through the plant is constant and the adsorber is functioning properly, a constant decrease in the slope would indicate decrease in concentration in the inflowing water. This could be due to either of the two reasons:

- General improvement in quality of water upgradient from the plant.
- Recirculation of the treated water through the aquifer in the vicinity of the plant.

The absence of any overall flattening of the slope on the cumulative recovery curve suggests that neither of these phenomenon are occurring. Examination of the potentiometric surface map during system operation indicates that no gradient is present that would cause recirculation.

5.3 RELIABILITY OF WATER QUALITY DATA

Examination of organic water quality analyses from monitoring wells shows that significant unexplained variation is present. Several of the monitoring wells show nearly order of magnitude fluctuations in concentration of DCPD and DIMP suggesting either sampling or analysis errors. Even though there is much variation in the data, the reliability is adequate to evaluate system performance when examined on an overall bases. A series of maps showing the concentration distribution at closely spaced times were constructed for DIMP, DCPD and chloride. The dates for the maps were chosen so a map prior to system installation and several maps during the operation of the pilot containment system could be examined and a comparison made. These maps are presented in terms of concentration bands that are generally based on linear interpolation between observed data points. It is noted that data is not available from identical sampling locations for each map.

5.4 EFFECT ON DIMP CONCENTRATIONS

The concentrations of DIMP prior to installation of the pilot containment system are shown in Figure 8. Three maps showing DIMP concentrations in September-October, November-December, and March are presented in Figures 16, 17, and 18 respectively. Concentrations after plant startup on the upgradient side remain relatively consistent. Trends are difficult to distinguish due to the fact that different wells were sampled at different times. Concentrations on the downgradient side of the barrier show the effects of recharge of treated water. The plume of low DIMP concentration spreads faster near the east end of the recharge line, based on the change in shape of the 0-500 concentration band between the presystem map (Figure 8) and the September-October, 1979 map (Figure 16). The November-December, 1978 map (Figure 17) shows some increase in concentrations in the central portion of the aquifer directly downgradient from the barrier and also a rise of lesser magnitude along the eastern edge. This rise in concentration may be due in part to the break-through of DIMP that occurred from mid-November to mid-December when output levels of DIMP from the carbon column ranged up to 500 $\mu g/\ell$. The March, 1979 concentration map (Figure 18) shows the effects of localized injection quite clearly. Nearly the entire flow of the plant was diverted to the three eastern recharge wells beginning in January. This resulted in a decrease in concentration downgradient of the three wells to a level only several times higher than the injected (treated) concentration. Concentrations on the west side of the pilot system showed an increase suggesting migration of contaminated water around the west end of the barrier.

5.5 EFFECT ON DCPD CONCENTRATIONS

As was predicted (McNeill, 1977), the present system does not intercept the main DCPD plume as shown on the preoperational concentration map (Figure 9). However, Figures 19 and 20 indicate diversion of part of a DCPD plume towards the pilot containment system area due to system operation. Figure 19 (September-October, 1978) shows concentrations three months after the plant was in operation. Comparison of Figures 9 and 19 show that in three months of operation the concentrations upgradient of the system have increased around the easternmost pumping wells but have been decreased immediately downgradient of the recharge system.

By March 1979 (Figure 20) DCPD plume was still moving towards the pilot plant although concentrations were decreasing slightly upgradient of the plant. Improvement in quality can be seen farther downgradient from the plant than on previous maps. Figure 20 illustrates a similar concentration pattern for DCPD as was observed for DIMP around the recharge wells for the period when all of the treated water was recharged through the three easternmost wells. In Figure 20, it can also be seen that the diverted DCPD plume is being moved downgradient from the dewatering wells.

5.6 CHLORIDE CONCENTRATION

Since the plant does not remove any chloride, this ion was used as a check to see if similar trends as those of DIMP and DCPD could be observed. Figure 10 shows chloride concentration prior to system operation. Relatively high concentration of chloride can be seen around the plant area just a week before the pilot plant started operation (July 25, 1978). Figure 21 (March 1979) shows chloride concentrations eight months after the system was in operation. High concentrations were still present around the pilot plant except immediately upgradient of the barrier and towards the west of the plant. This low concentration is possibly due to movements of fresh water from a source to the west towards the plant due to the dewatering system.

A monitoring well located about 3,500 feet northwest of the plant (Well No. 313) shows improvement in quality both in chloride and DIMP (Figures 18 and 21). The simultaneous improvement in these components may suggest local recharge dilution. It is doubtful that the operation of the plant has affected this well as theoretical computations show that it would take more than one year for any effect to be seen in this well. In future years the chloride distribution may be valuable for illustrating regional flow system changes.

5.7 DISCREPANCIES IN THE WATER QUALITY DATA

If the pilot containment system was functioning properly, a decline in the DIMP and DCPD values for wells located downgradient from the recharge wells would be expected. As can be seen in Figures 8, 18, 9, and 20 there has been an improvement in quality in the wells located immediately downgradient from the recharge wells. Monitoring wells located further away show little or no measurable improvement up to this time.

Some concern has been expressed as to why the quality data, particularly DIMP, for downgradient wells does not show a continuous improvement in quality. The apparent inconsistancies in the data may be explained by changes in the plant operation. In November and December, 1978 the activated carbon filter had a "break through" and significantly less DIMP was removed by the adsorber during this period. This resulted in a rise in DIMP values in downgradient wells as compared to the September-October (1978) data (Figures 16 and 17).

Beginning in January 1979, all of the recharge was placed in the three eastern wells. This resulted in higher water levels in this area (Figure 14) as compared with the previous potentiometric surface (Figure 13). As the treated water was still being recharged in the eastern wells, the wells downgradient show low DIMP and DCPD values (Figures 18 and 20). The wells located downgradient from the inoperative recharge wells exhibit a definite rise in contaminant levels. This indicates that some contaminated water is flowing around the barrier along the western edge of the impermeable barrier.

A theoretical pollutant movement calculation was made to determine the temporal position of a broad front plume of treated water (Bouwer, 1978). The dispersion equation allows estimation of concentration when groundwater velocity and dispersion coefficients are known. The dispersion equation allows for the fact that the plume does not move as a unit with a sharp concentration boundary between contaminated and treated water. Dispersion coefficients for the alluvial aquifer were from work conducted by Robson (1977). The results of these calculations are provided in Figure 22. The equations are set up so the water in the treated plume is treated as a tracer concentration. The uppermost curve for a resultant concentrate of 1.1×10^{-5} times the input concentration can be taken as the first arrival of trace amounts of the treated effluent. In a practical sense, concentrations of this magnitude cannot be detected. The middle curve shows the arrival of the 50 percent concentration line, i.e., water at the observation point consists of 1/2 water at the initial concentration and 1/2 at the treated plume concentration. The lower curve shows concentration levels equal to input concentration signifing complete flushing of the aquifer with treated effluent. These long travel times partially explain why little general improvement in water quality has taken place on the downgradient side of the pilot containment system.

Due to the number of complicating factors involving the concentrations of contaminants in wells downgradient of the barrier, it is not prudent to determine if the system is functioning properly by doing a statistical analysis on the water quality data. Changes in plant operation, diversion of contaminated water around the barrier, and long pollutant travel times obscure any statistical trends that may show improvement in quality.

6.0 CONCLUSIONS

Based on the following reasons, it is concluded that the north boundary pilot containment system is removing contaminated water from the aquifer, removing the organic contaminants, and returning the treated water to the aquifer:

- The plumes of treated water correspond with the location of the recharge points.
- The cumulative recovery graphs show a continued recovery of contaminents in the treatment plant over the period of operations.
- A DCPD plume has been diverted into the dewatering wells but no corresponding increase in DCPD is noted in the wells downgradient of the recharge wells. Arrival of this plume at the plant is marked by the increase in early September of the slope of the cumulative recovery graph.
- Theoretical dispersion calculations show that no dramatic improvement in downgradient water quality is expected after only one year of operation.

For the following reasons it is concluded that the pilot containment system is not diverting the entire flow of the aquifer that was flowing across the barrier alignment through the treatment plant:

- The water level contours show an increase in gradient around the edge of the barrier indicating an increase in flow.
- The total volume of water being pumped by the dewatering wells is only about 30 percent of the total flow through this section of aquifer based on our estimates.
- The concentrations of contaminants increased in wells downgradient of the westernmost recharge wells when the flow to those recharge wells was stopped as it was in January 1979. This indicates migration around the western edge of the barrier is taking place.

- The concentration map for DCPD of March 1979 (Figure 17) shows the plume that was deflected into the dewatering wells is being diverted around the barrier to the recharge side.

Respectfully submitted,

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TABLES

TABLE 1

PREDICTED DRAWDOWNS[1]
AND ACTUAL DRAWDOWNS
AFTER 10 DAYS OF OPERATION

WELL NO.	PREDICTED		ACTUAL	
	DRAWDOWN (ft)	FLOW RATE (gpm)	DRAWDOWN (ft)	AVERAGE FLOW RATE (gpm)
321	2.5	4	1.29	1.4
320	3.3	5	3.15	4.8
319	3.5	14	2.28	10.2
318	3.5	14	1.52	5.3
317	3.2	16	1.63	12.2
316	2.6	17	1.38	12.9

[1] Kolmer and Anderson, 1977.

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TABLE 2

MODIFIED DESIGN PREDICTIONS OF
DRAWDOWN BASED ON ACTUAL PUMPING RATES
COMPARED WITH OBSERVED DRAWDOWNS

WELL NO.	ACTUAL PUMPING RATE (gpm)	MODIFIED DRAWDOWN(1) PREDICTION		OBSERVED DRAWDOWN 10 days
		7 days	10 days	
321	1.4	1.3	1.6	1.29
320	4.8	2.3	2.6	3.15
319	10.2	3.9	4.3	2.28
318	5.3	2.1	2.5	1.52
317	12.2	2.1	2.5	1.63
316	12.9	2.4	2.7	1.38

(1)Prediction based on Theis equation using actual pumping rates.

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TABLE 3

WELL SIMULATOR INPUT DATA FOR 60 DAYS OF OPERATION

WELL NO.	CARTESIAN COORDINATES X	Y	FLOW RATE (gpm)	OBSERVATION POINT RADIUS[1] (ft)	SATURATED THICKNESS (ft)	PERMEABILITY (gpd/ft^2)	TRANSMISSIVITY (gpd/ft)	STORAGE COEF.
321	-	-	1.5	2.5	3.0	1,500	4,500	.10
320	230	-	5.0	2.5	5.0	1,200	6,000	.10
319	462	-	6.0	2.5	3.0	4,000	12,000	.10
318	690	-	11.0	2.5	8.0	3,000	24,000	.10
317	925	-	19.5	2.5	12.0	2,500	30,000	.10
316	1153	-	20.0	2.5	7.0	3,400	23,975	.10
321i	-	508	1.5	2.5	3.0	1,500	4,500	.10
320i	230	508	5.0	2.5	5.0	1,200	6,000	.10
319i	462	508	6.0	2.5	3.0	4,000	12,000	.10
318i	690	508	11.0	2.5	8.0	3,000	24,000	.10
317i	925	508	19.5	2.5	12.0	2,500	30,000	.10
316i	1153	508	20.0	2.5	7.0	3,400	23,975	.10
OP 1	500	-100	-	-	8.0	3,000	24,000	.10
OP 2	500	-250	-	-	8.0	3,000	24,000	.10
OP 3	500	-500	-	-	8.0	3,000	24,000	.10
OP 4	500	-1000	-	-	8.0	3,000	24,000	.10
OP 5	500	-2500	-	-	8.0	3,000	24,000	.10
OP 6	500	-3000	-	-	8.0	3,000	24,000	.10
OP 7	500	-3500	-	-	8.0	3,000	24,000	.10
OP 8	500	-4000	-	-	8.0	3,000	24,000	.10
OP 9	500	-5000	-	-	8.0	3,000	24,000	.10

(1) Observation radius is at closest observation point to dewatering well and is taken as the water level in the pumping well.

OP 1 - Observation Point No. 1 (theoretical locations).

See Figure 11 for location of wells and coordinate axes.

TABLE 4

COMPARISON OF ACTUAL
AND PREDICTED DRAWDOWNS
AFTER 60 DAYS OF OPERATION

WELL NO.	PREDICTED DRAWDOWN (ft)	ACTUAL DRAWDOWN (ft)
321	1.9	1.78
320	2.9	3.41 (1)
319	2.7	2.65
318	2.6	2.97
317	2.8	3.15
316	2.9	2.74
OP 1	2.1	- (2)
OP 2	1.7	- (2)
OP 3	1.3	- (2)
OP 4	0.7	- (2)
OP 5	0.1	- (2)
OP 6	0.1	- (2)
OP 7	0.0	- (2)
OP 8	0.0	- (2)
OP 9	0.0	- (2)

(1) Excess drawdown may be due to well losses.

(2) Actual drawdown not quantified due to fluctuations in groundwater levels.

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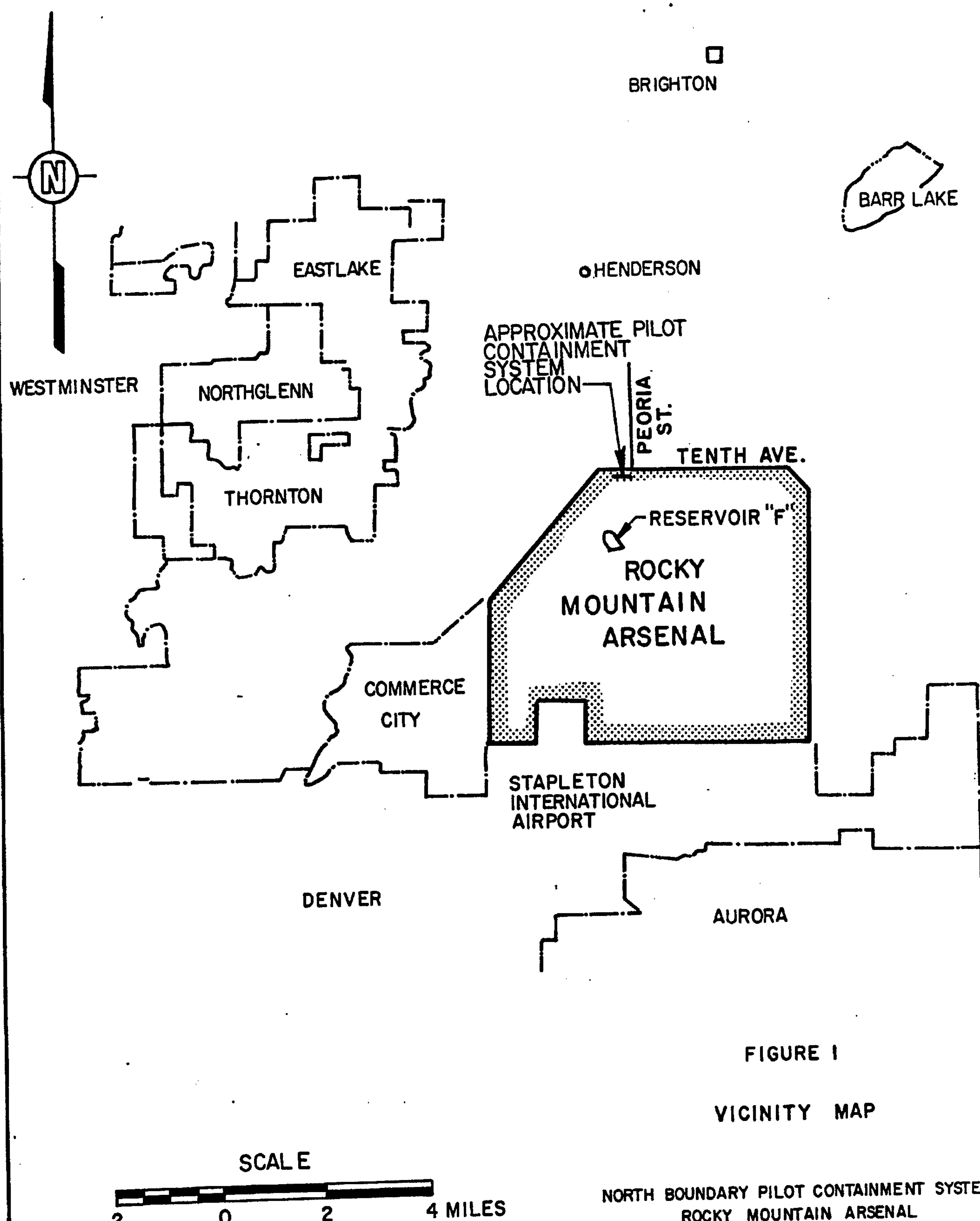
FIGURES



DRAWN BY S.L.T. 7-5-79
CHECKED BY
APPROVED BY JCM
DRAWING NUMBER 79-389-A3

FIGURE 1

VICINITY MAP

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

REFERENCE:
KOLMER AND ANDERSON, 1977B.

DRAWN BY B.K.H. 6-29-79 CHECKED BY APPROVED BY DRAWING NUMBER R. 3-389-A2

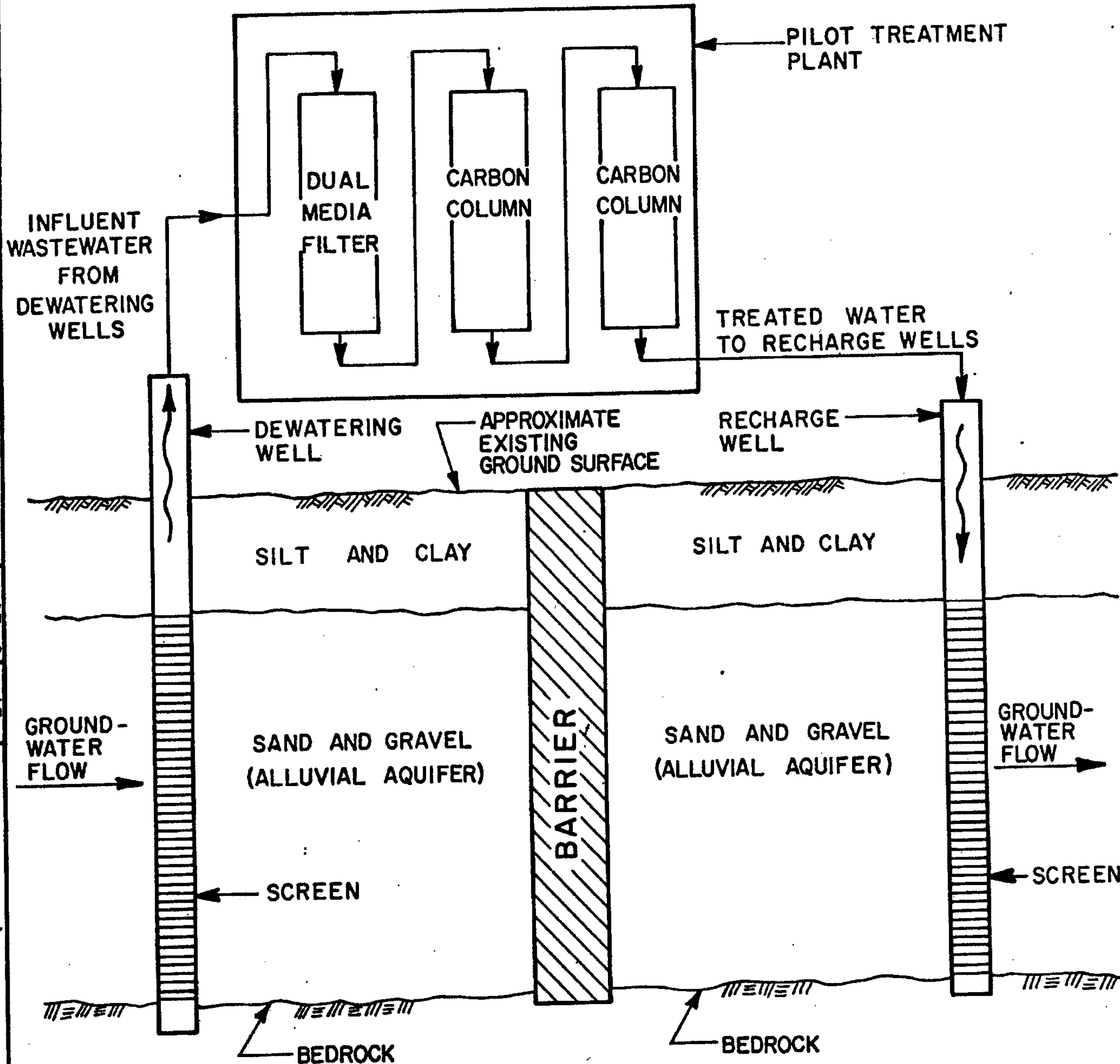


FIGURE 2

SCHEMATIC DIAGRAM OF PILOT CONTAINMENT SYSTEM

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

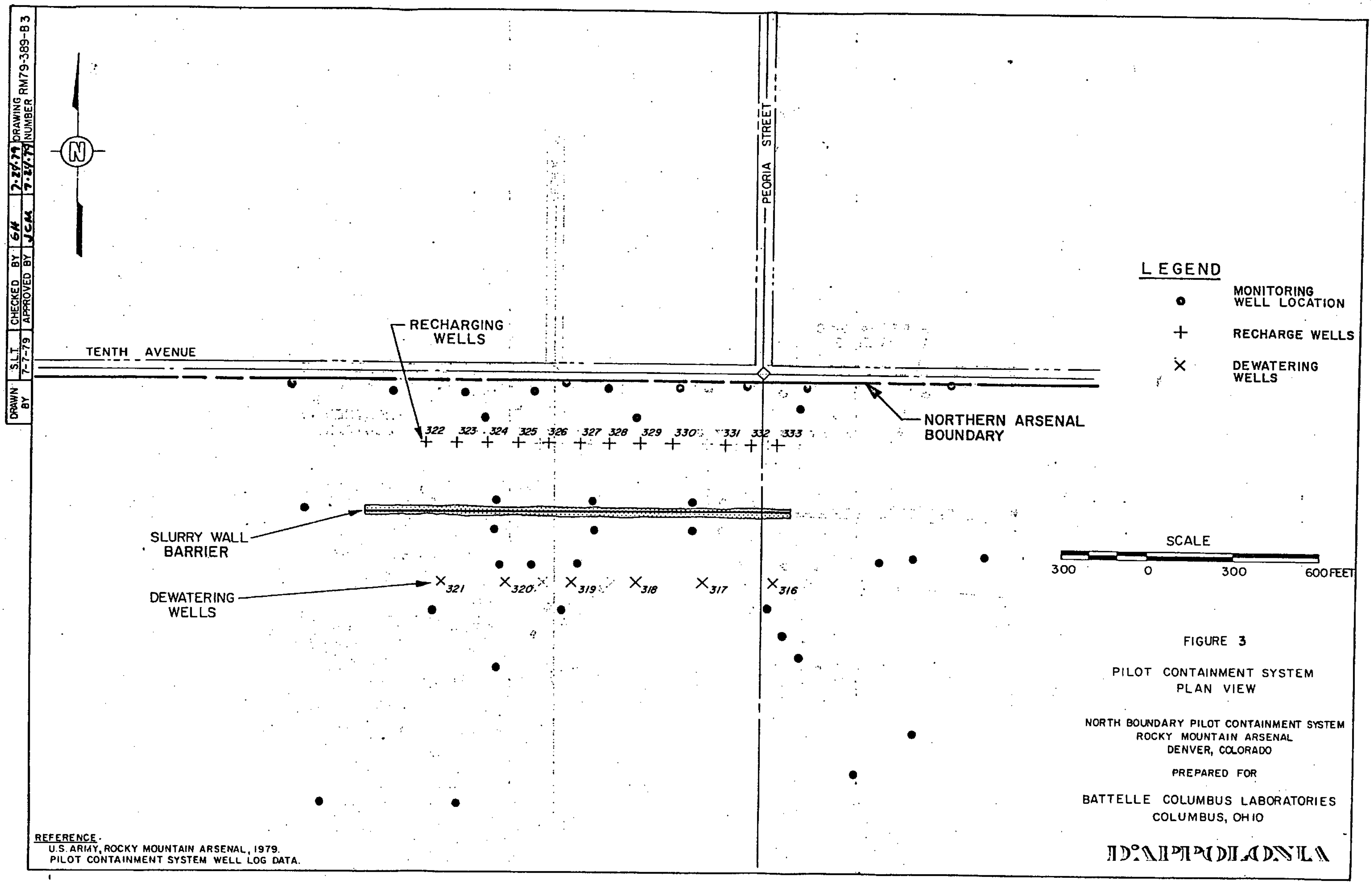


FIGURE 3

PILOT CONTAINMENT SYSTEM
PLAN VIEW

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

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REFERENCE:
U.S. ARMY, ROCKY MOUNTAIN ARSENAL, 1979.
PILOT CONTAINMENT SYSTEM WELL LOG DATA.

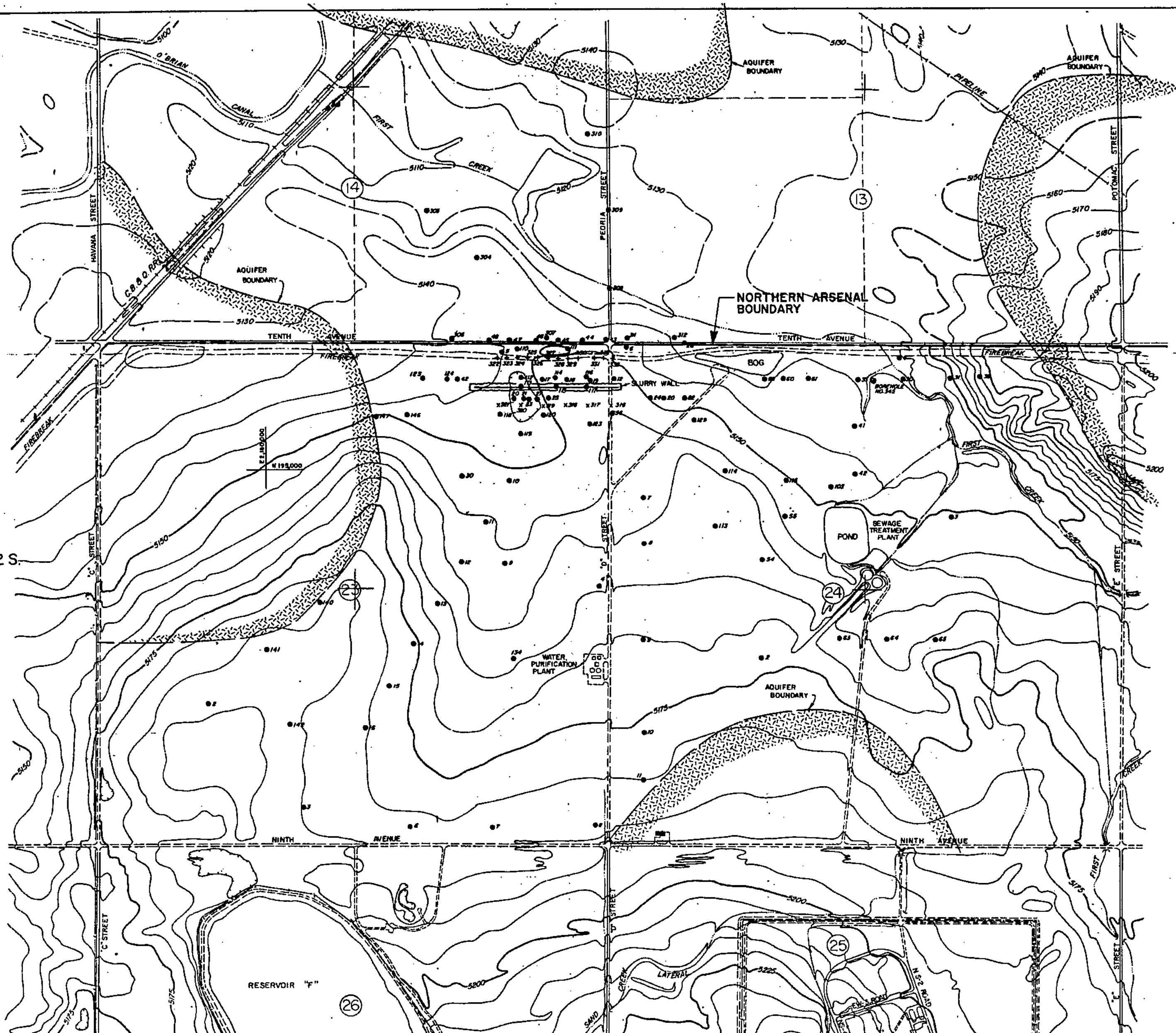

FIGURE 4

MONITORING WELL LOCATIONS

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE 1965 SCALE 1:24000

DRAWN BY	M. K.	CHECKED BY	JCH	DRAWING NUMBER	RM79-389-E12
	6-29-79	APPROVED BY		7-24-79	

007016-00 (1)

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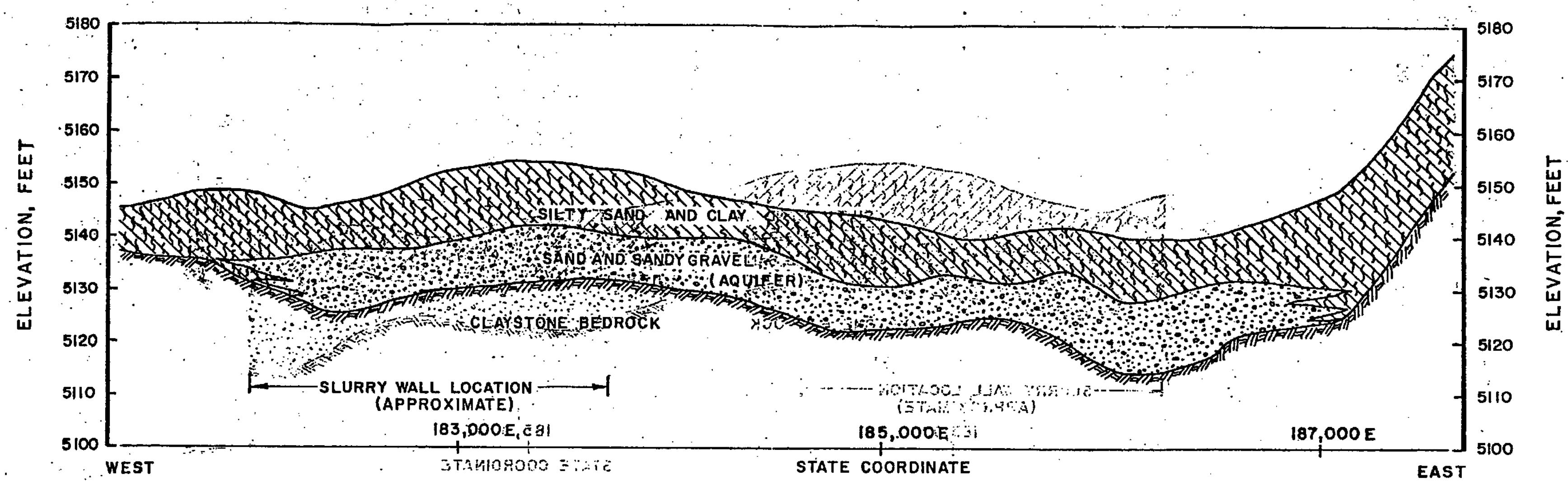

CROSS-SECTION
(LOOKING NORTH)

VERTICAL SCALE
20 0 20 40 FEET

HORIZONTAL SCALE
500 0 500 1000 FEET

REFERENCE:
U.S. ARMY, ROCKY MOUNTAIN ARSENAL, BORING LOGS FOR WELLS NORTH OF COORDINATE N 193000, UNPUBLISHED BASIC DATA.

FIGURE 5
DIAGRAMATIC GEOLOGIC CROSS-SECTION IN THE VICINITY OF THE NORTH ARSENAL BOUNDARY

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

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	7-17-79	APPROVED BY	JCM	7-24-79		

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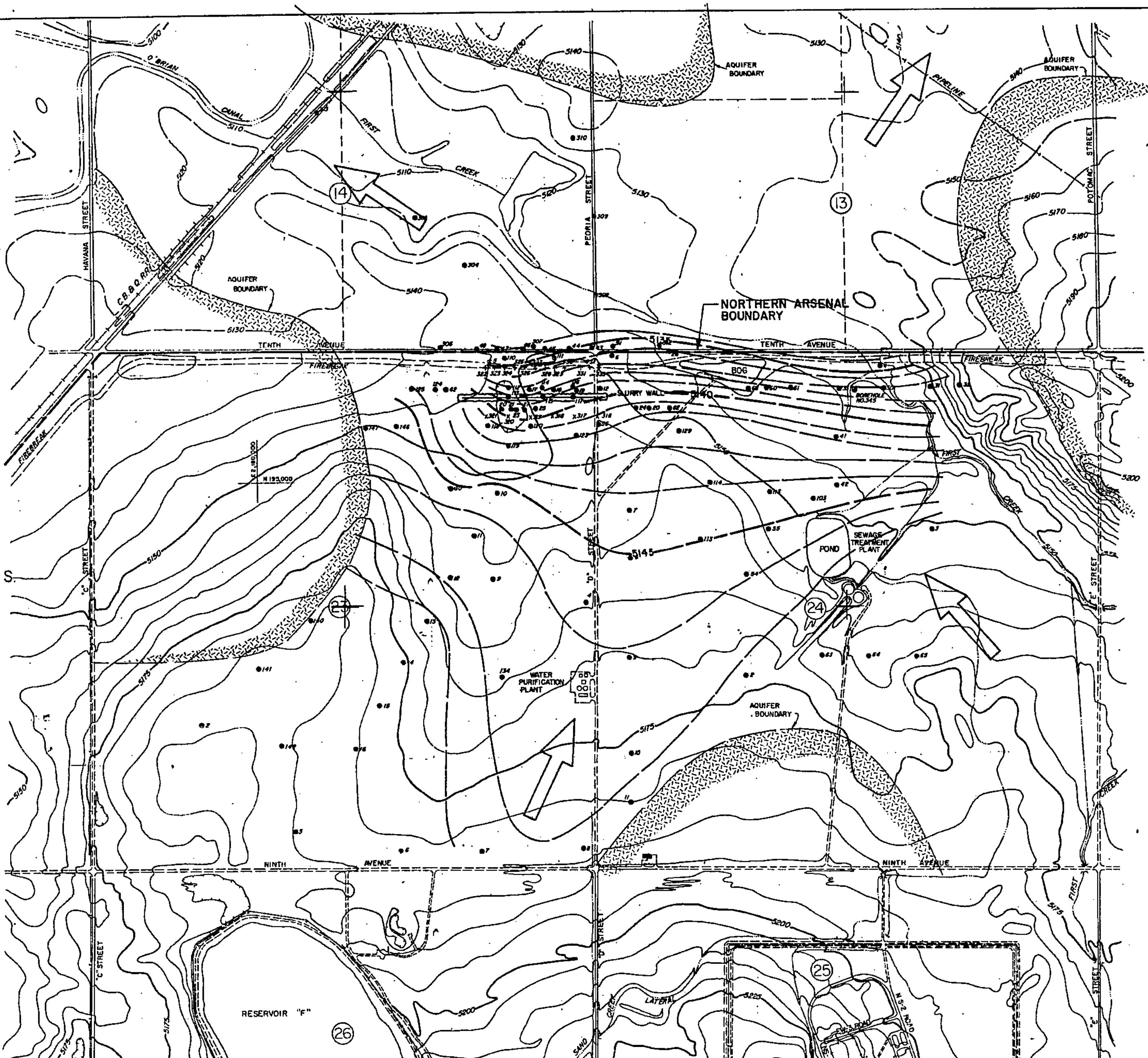

LEGEND

- MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)
- RECHARGING WELL
- DEWATERING WELL
- 5135 APPROXIMATE POTENTIOMETRIC SURFACE CONTOUR (DATUM MEAN SEA LEVEL)
- DIRECTION OF GROUNDWATER FLOW (ROBSON, 1976)
- BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)
- CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)
- CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)

NOTE: POTENTIOMETRIC SURFACE MAP DEVELOPED USING WATER LEVEL DATA FOR FEBRUARY AND MARCH, 1978.

SCALE

500 0 500 1000 FEET

POTENTIOMETRIC CONTOUR INTERVAL = 1 FOOT

FIGURE 6

POTENTIOMETRIC SURFACE MAP PRESYSTEM

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE = 1:24000

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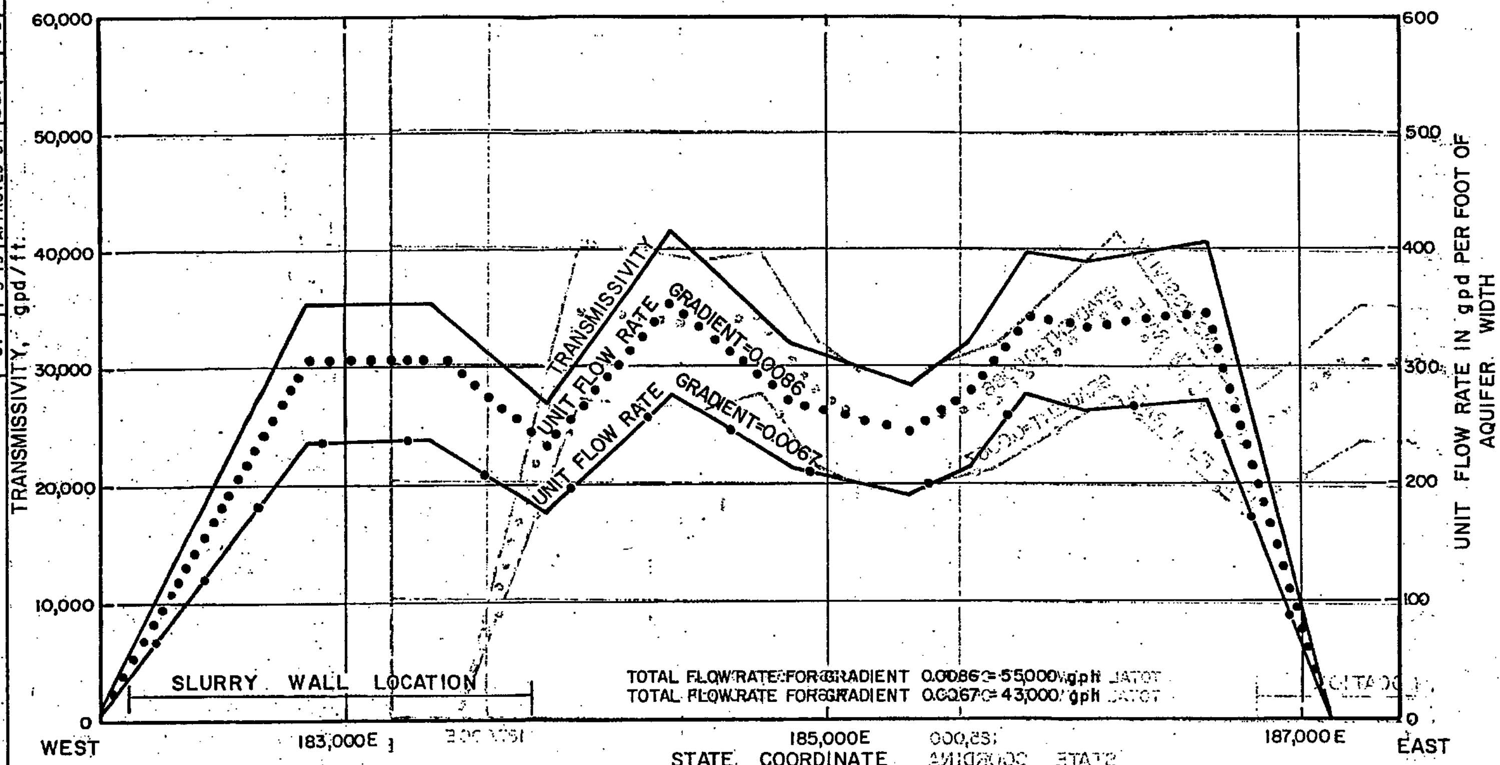
B7900065 (2)



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		APPROVED BY	JCH 7-27-79	RM79-389-B1

NOTES: 1. TRANSMISSIVITY $= K_{sand} \cdot M_{sand} + K_{sand\ and\ gravel} \cdot M_{sand\ and\ gravel}$

WHERE K = PERMEABILITY

M = SATURATED THICKNESS UNDER AVERAGE CONDITIONS.

2. TOTAL FLOW IS EQUAL TO THE AREA UNDER A SPECIFIC FLOW RATE CURVE.

FIGURE 7.

AQUIFER TRANSMISSIVITY AND FLOW RATES ACROSS NORTHERN ARSENAL BOUNDARY

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

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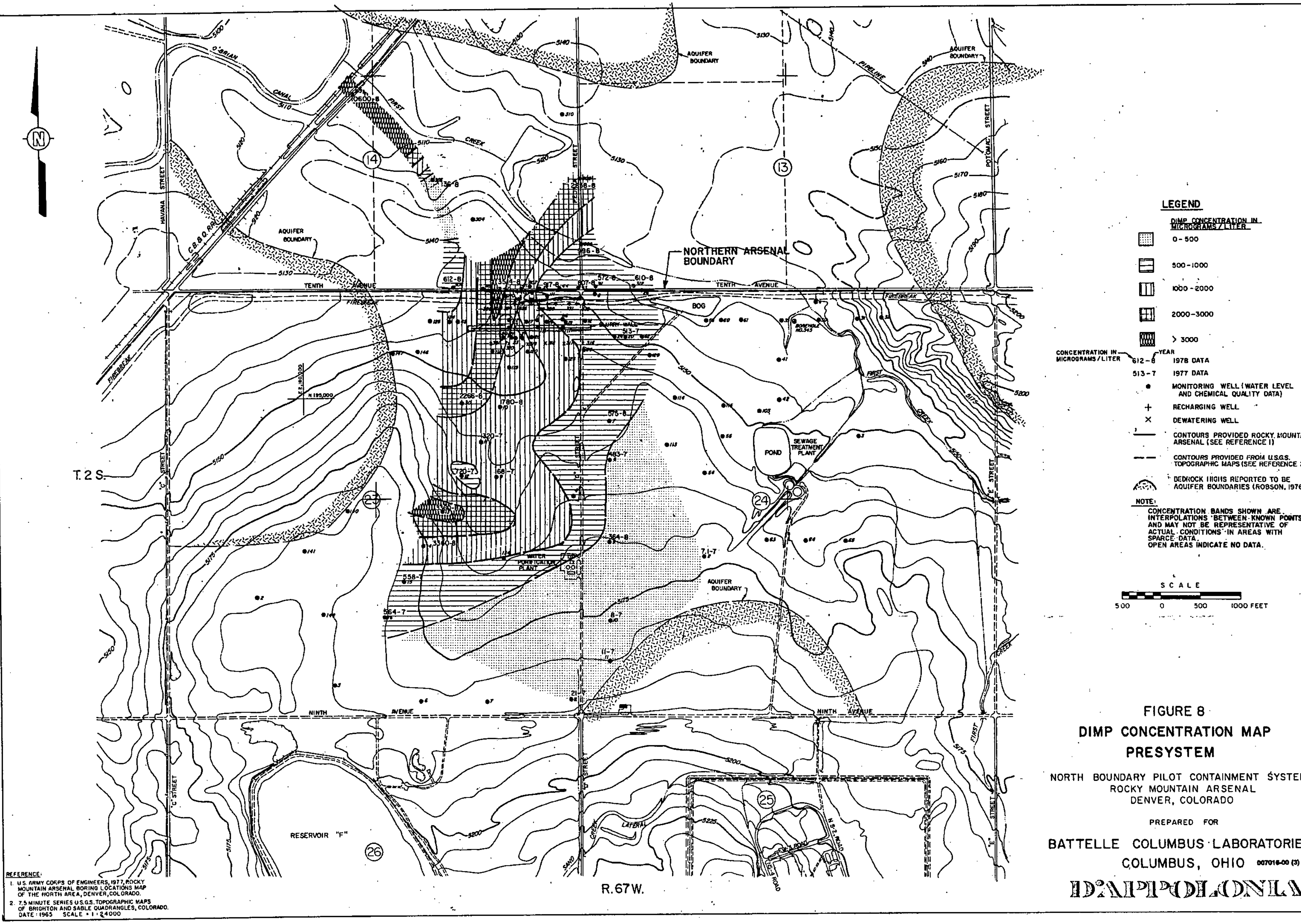

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	6-30-79	APPROVED BY	JCM	7.24.79		

FIGURE 8

DIMP CONCENTRATION MAP PRESYSTEM

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

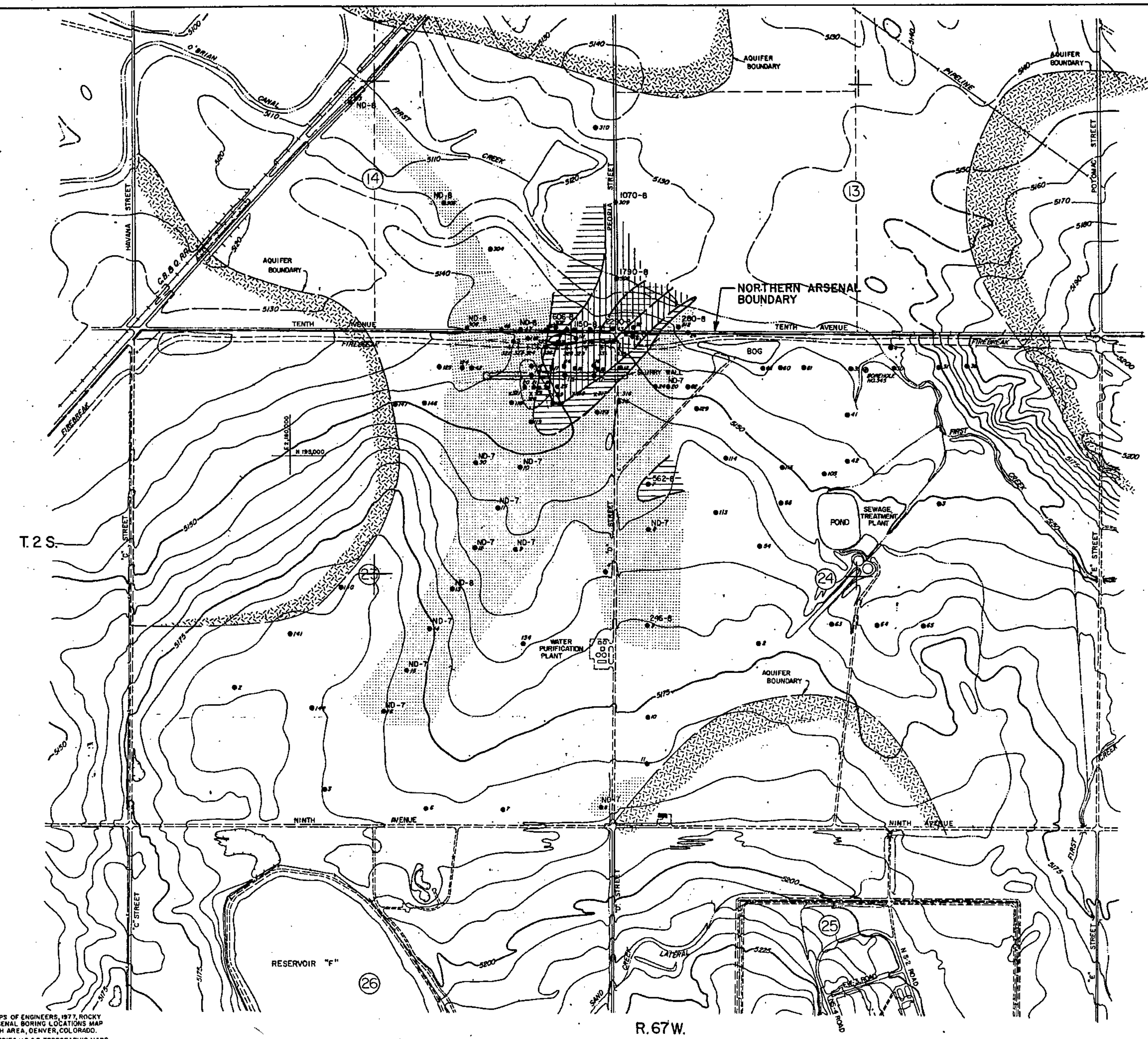
PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO 007016-00 (3)

D'APPOLONIA

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE 1:24000

87900055 (3)



LEGEND

DCPD CONCENTRATION IN MICROGRAMS/LITER

- 0-500
- 500-1000
- 1000-2000
- > 2000

CONCENTRATION IN MICROGRAMS/LITER — 562-8 — YEAR
562-8 1978 DATA
ND-7 1977 DATA

- ● MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)
- + RECHARGING WELL
- × DEWATERING WELL
- ND NONE DETECTED
- CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)
- CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)
- BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)

NOTE:
CONCENTRATION BANDS SHOWN ARE INTERPOLATIONS BETWEEN KNOWN POINTS AND MAY NOT BE REPRESENTATIVE OF ACTUAL CONDITIONS IN AREAS WITH SPARCE DATA.
OPEN AREAS INDICATE NO DATA.

SCALE
500 0 500 1000 FEET

FIGURE 9
DCPD CONCENTRATION MAP PRESYSTEM

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

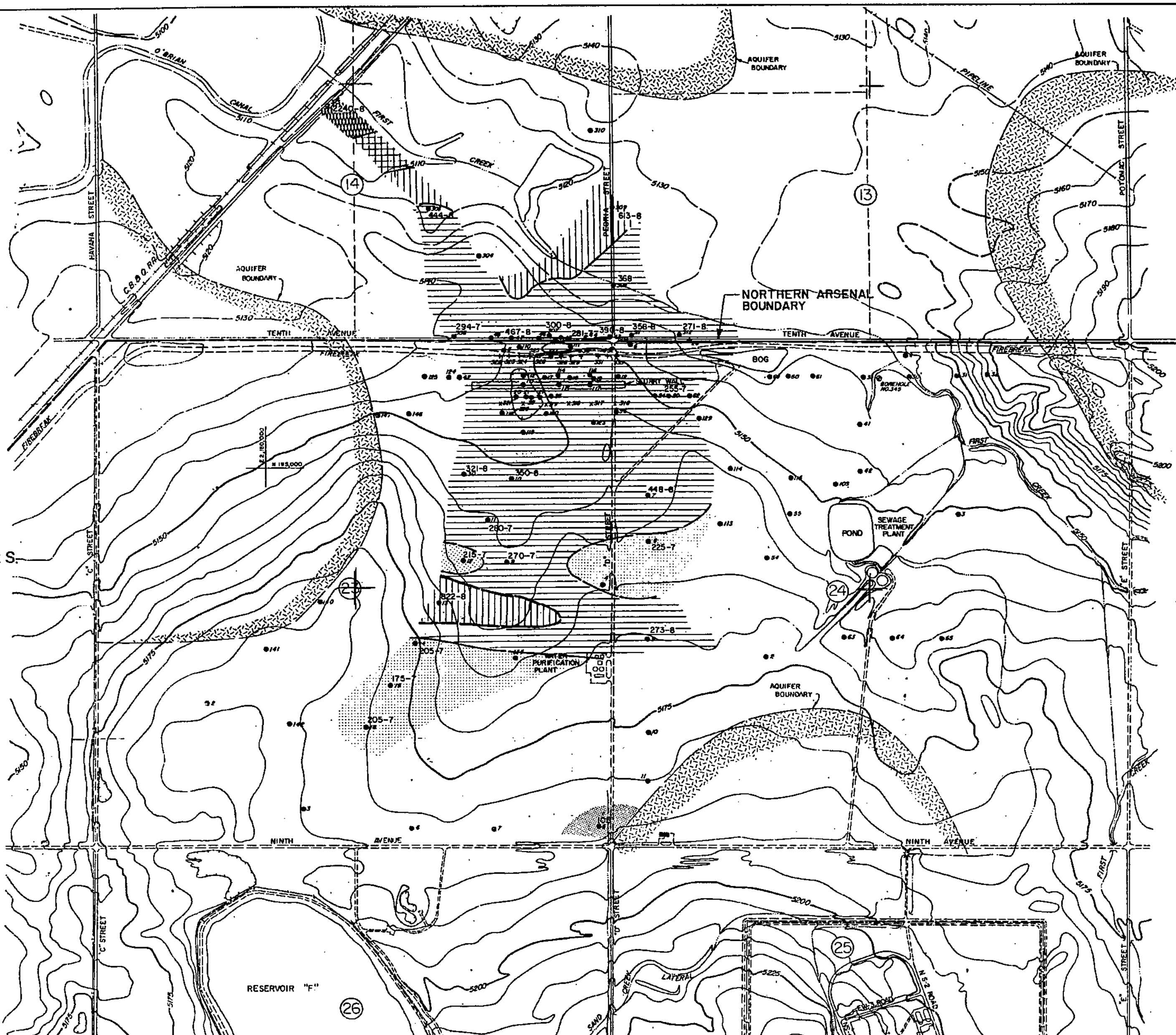
D'APPOLONIA

007016-00 (4)

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE 1965 SCALE 1:24000

DRAWN BY	S.L.T.	6-30-79
CHECKED BY	R.R. Hemp	7/6/79
APPROVED BY	JCM	7/24/79
DRAWING NUMBER	RM79-389-E-4	

B7900055 (4)



LEGEND

CHLORIDE CONCENTRATION IN MILLIGRAMS/LITER

- 0 - 250
- 250 - 500
- 500 - 1000
- 1000 - 2000
- > 2000

CONCENTRATION IN MILLIGRAMS/LITER — 350-8 — YEAR 1978 DATA

225-7 1977 DATA

- ● MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)
- + RECHARGING WELL
- × DEWATERING WELL
- CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)
- CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)
- BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)

NOTE: CONCENTRATION BANDS SHOWN ARE INTERPOLATIONS BETWEEN KNOWN POINTS AND MAY NOT BE REPRESENTATIVE OF ACTUAL CONDITIONS IN AREAS WITH SPARCE DATA. OPEN AREAS INDICATE NO DATA.

SCALE 500 0 500 1000 FEET

FIGURE 10

CHLORIDE CONCENTRATION MAP PRESYSTEM

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO 007016-00 (5)

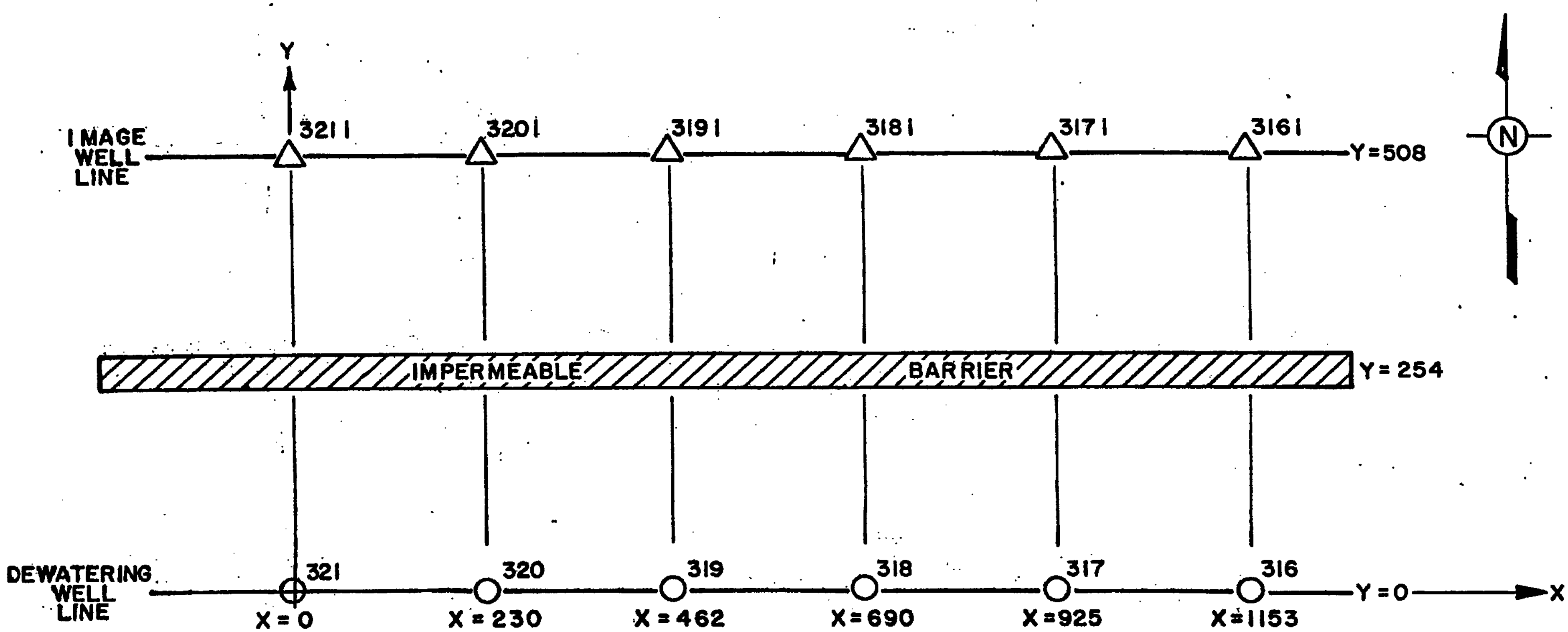
D'APPOLONIA

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE = 1:24000

DRAWN BY	S.L.T.	CHECKED BY	[signature] 7/6/79	DRAWING NUMBER	RM79-389-E6
	6-30-79	APPROVED BY	JCM 7/24/79		

87900055 (6)

BY 7-2-79 APPROVED BY JCM 7-25-79 NUMBER 9-389-A1



NOTE: BARRIER WIDTH NOT TO SCALE

SCALE

100 0 100 200 FEET

FIGURE 11

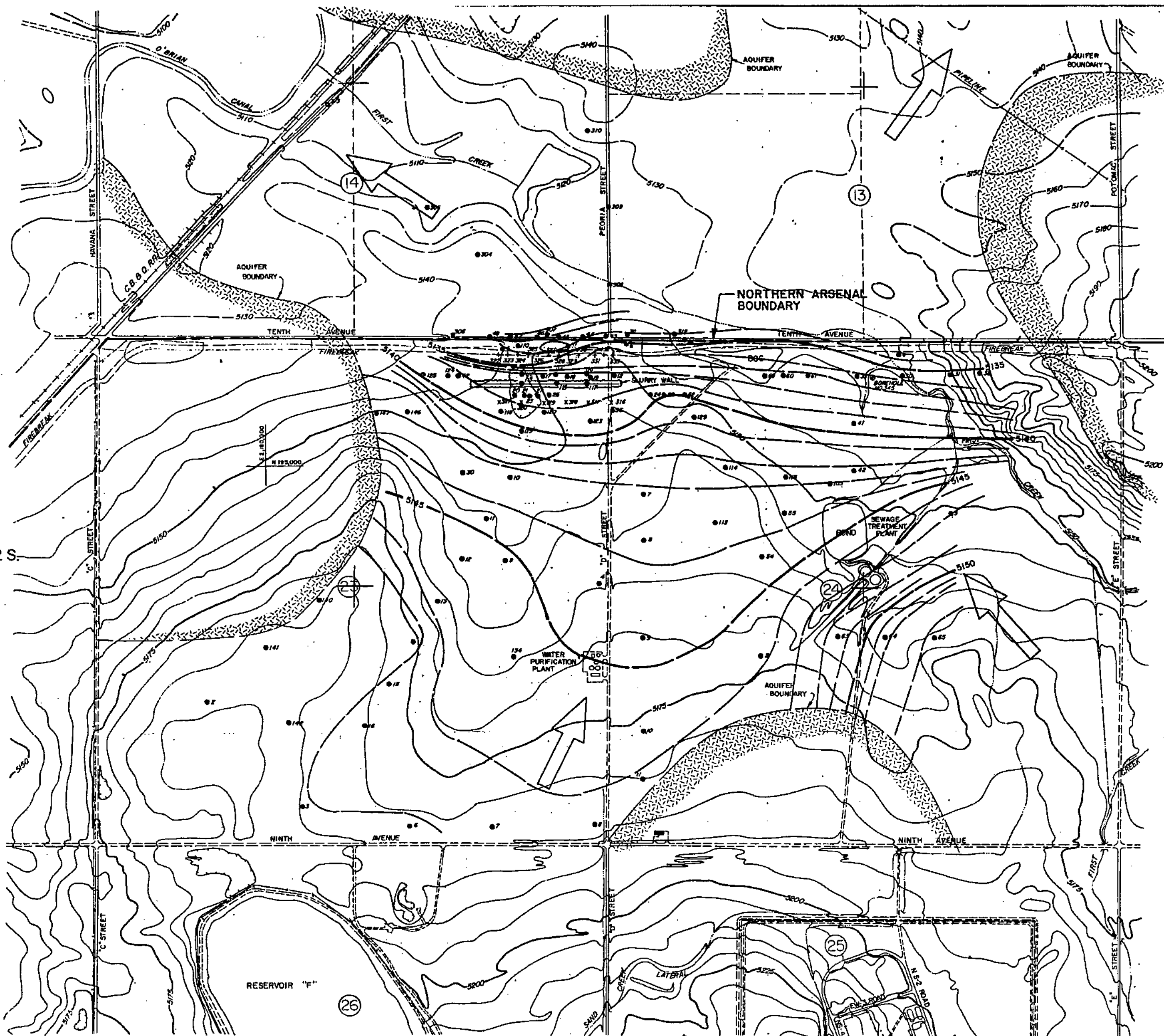
DEWATERING SIMULATION
WELL LOCATION

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA



LEGEND

- • MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)
- + RECHARGING WELL
- × DEWATERING WELL
- 5135 APPROXIMATE POTETIOMETRIC SURFACE CONTOUR (DATUM MEAN SEA LEVEL)
- DIRECTION OF GROUNDWATER FLOW (ROBSON, 1976)
- CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)
- CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)
- BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)

NOTE: OPEN AREAS INDICATE NO DATA.

SCALE

500 0 500 1000 FEET

POTENTIOMETRIC CONTOUR INTERVAL = 1 FOOT

FIGURE 12

POTENTIOMETRIC SURFACE MAP SEPTEMBER – OCTOBER, 1978

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

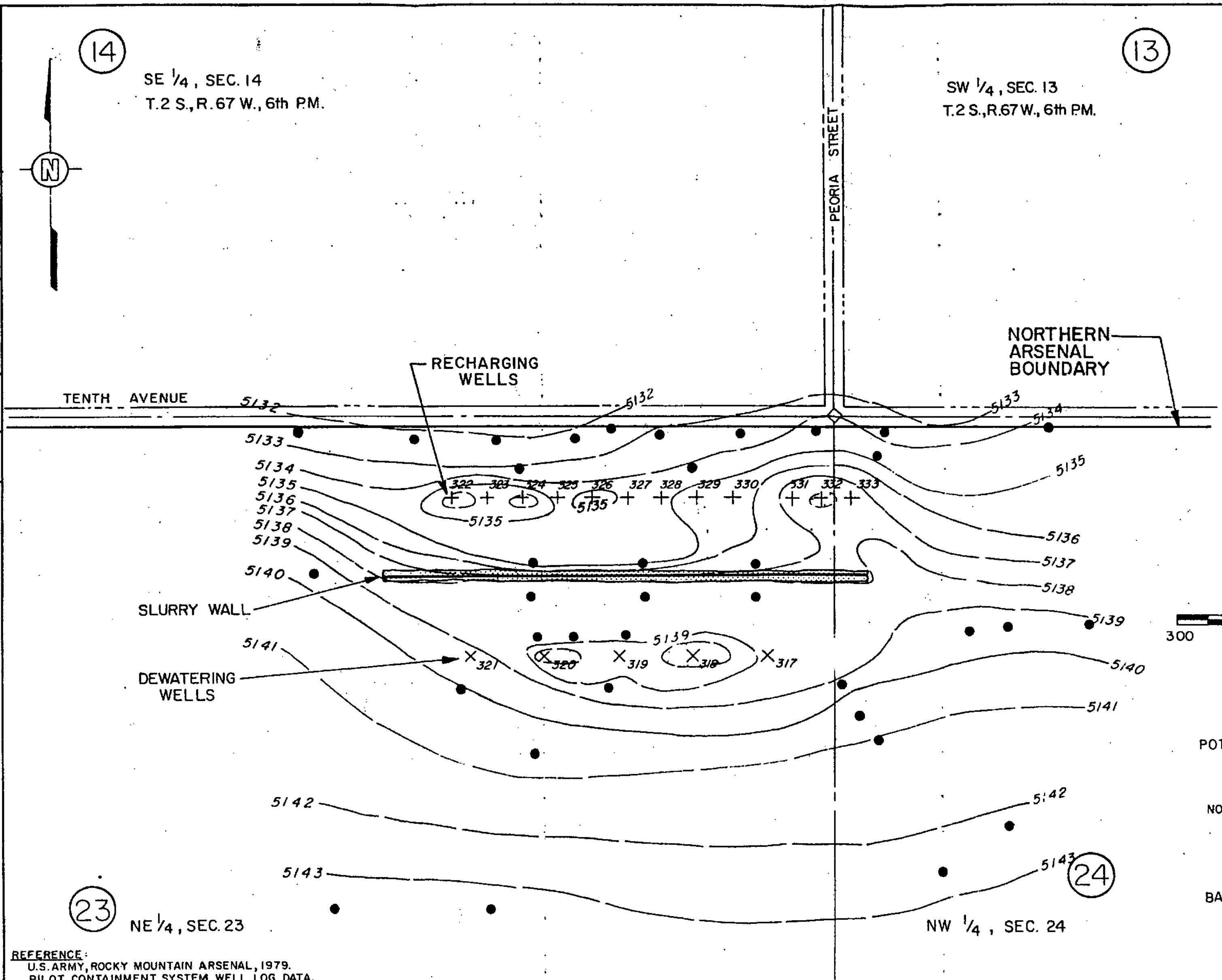
D'APPOLONIA

007018-00 (6)

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE = 1:24000

DRAWN BY	S.L.T.	CHECKED BY	M.C.Uhner	7/6/79	DRAWING NUMBER
	6-30-79	APPROVED BY	JCM	7-24-79	RM79-389-E2

87900065 (6)



DRAWN BY	S.L.T.	CHECKED BY	GRH	7-25-79	DRAWING NUMBER RM79-389-86
	7-7-79	APPROVED BY	JCM	7-25-79	

LEGEND

● WELL LOCATION

5134 WATER LEVEL CONTOUR DATUM MEAN SEA LEVEL

NOTE: RECHARGE OCCURRING AT WELLS 322 THROUGH 333.

SCALE

300 0 300 600 FEET

FIGURE 13

POTENTIOMETRIC SURFACE CONTOUR MAP
PILOT SYSTEM DETAIL
SEPTEMBER - OCTOBER, 1978

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

REFERENCE:
U.S. ARMY, ROCKY MOUNTAIN ARSENAL, 1979.
PILOT CONTAINMENT SYSTEM WELL LOG DATA.

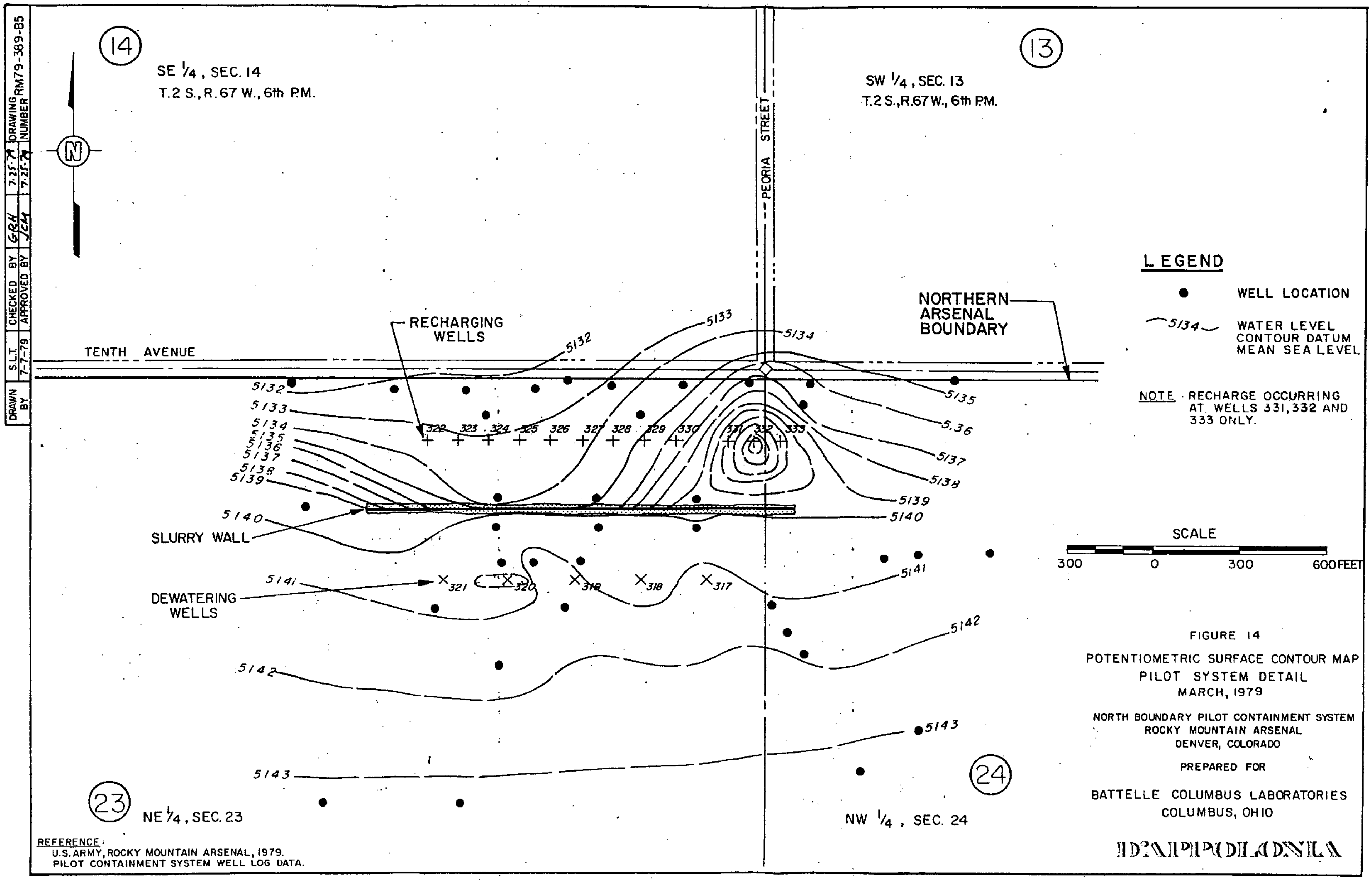


FIGURE 14
POTENTIOMETRIC SURFACE CONTOUR MAP
PILOT SYSTEM DETAIL
MARCH, 1979

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

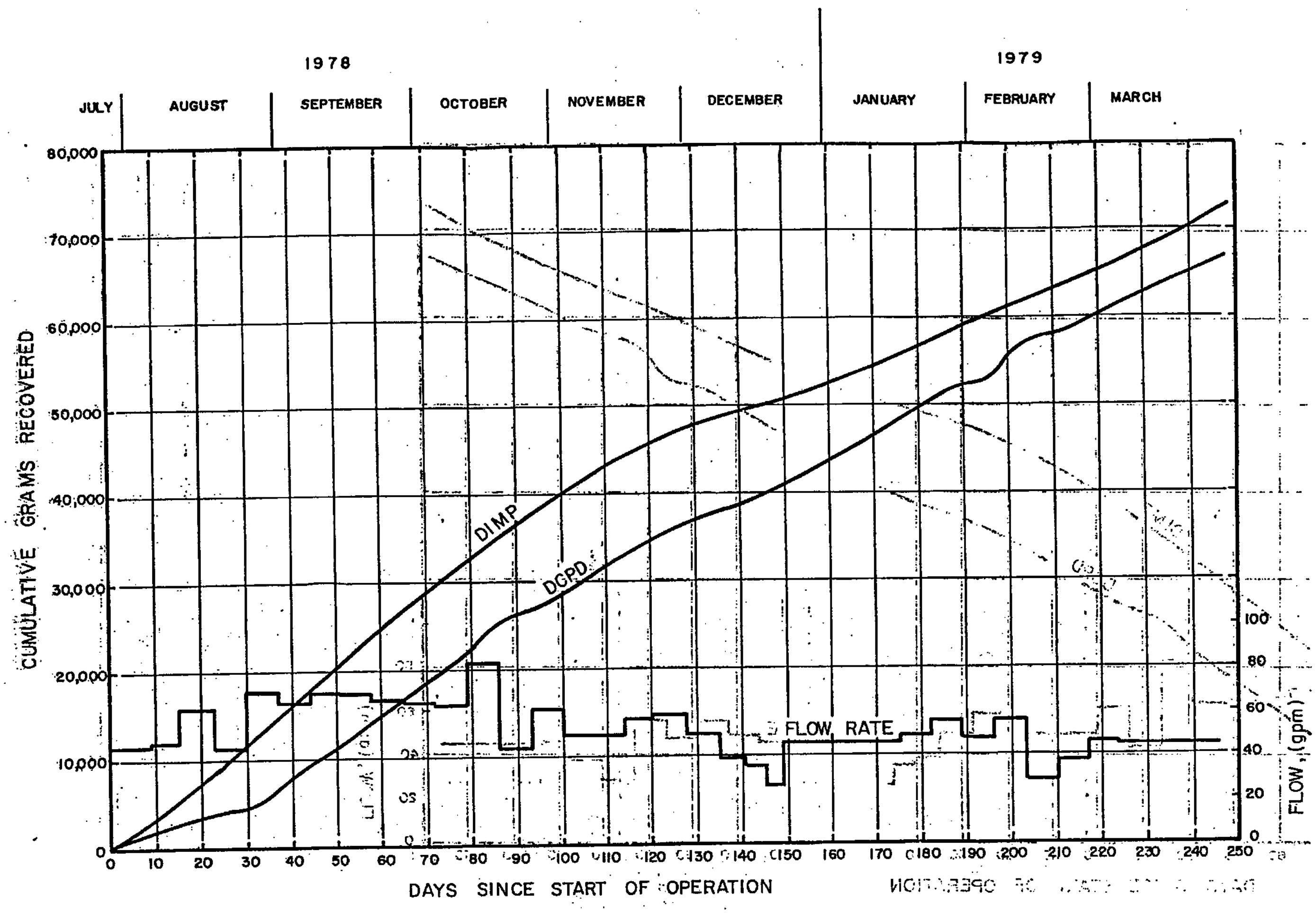


FIGURE 15

CUMULATIVE RECOVERY
FLOW RATE GRAPHS

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

DRAWN BY	S.L.T. 7-5-79	CHECKED BY	G.B.R. 7-23-79	DRAWING NUMBER	RM79-389-82
		APPROVED BY	[illegible] 7-25-79		

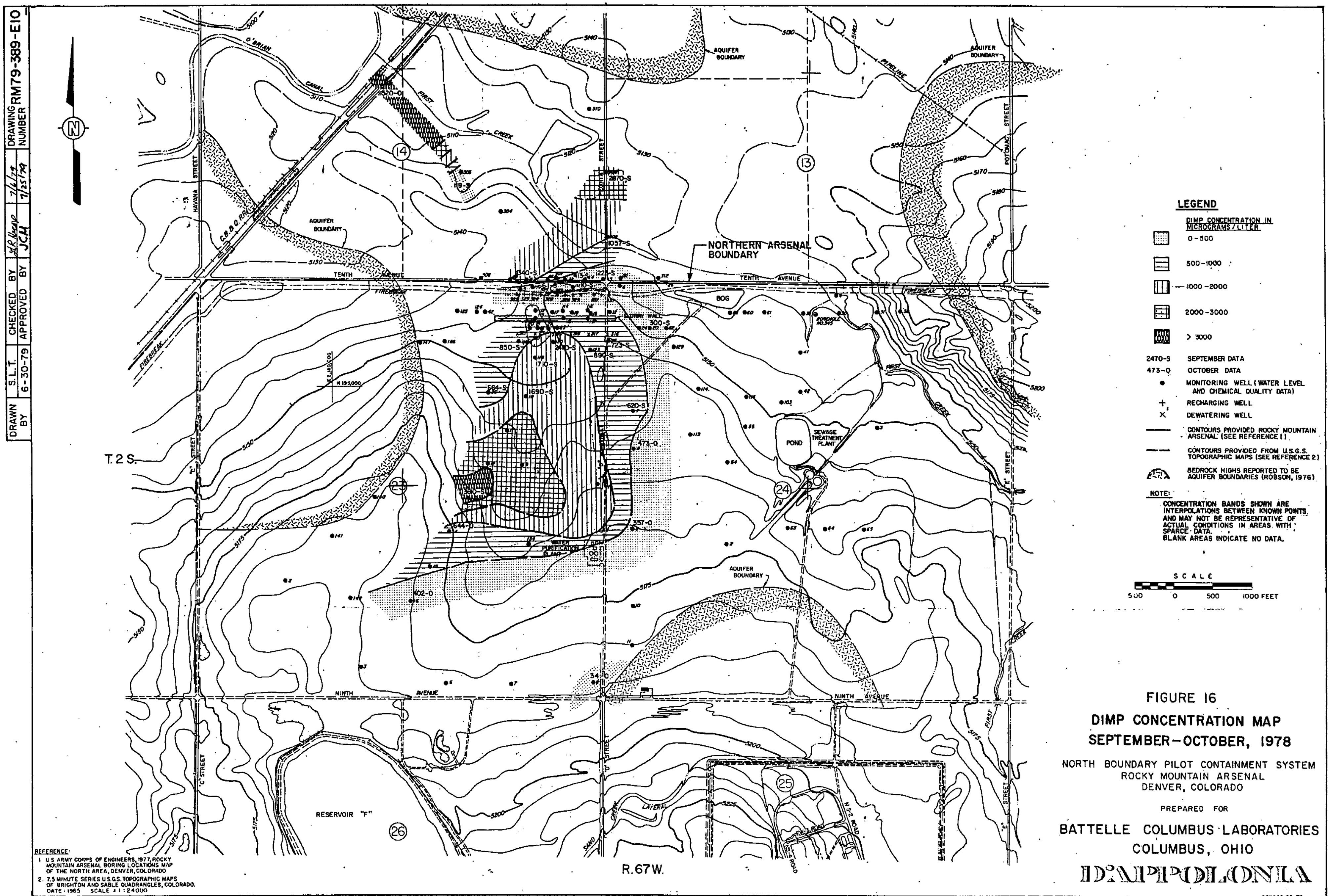


FIGURE 16

DIMP CONCENTRATION MAP SEPTEMBER–OCTOBER, 1978

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

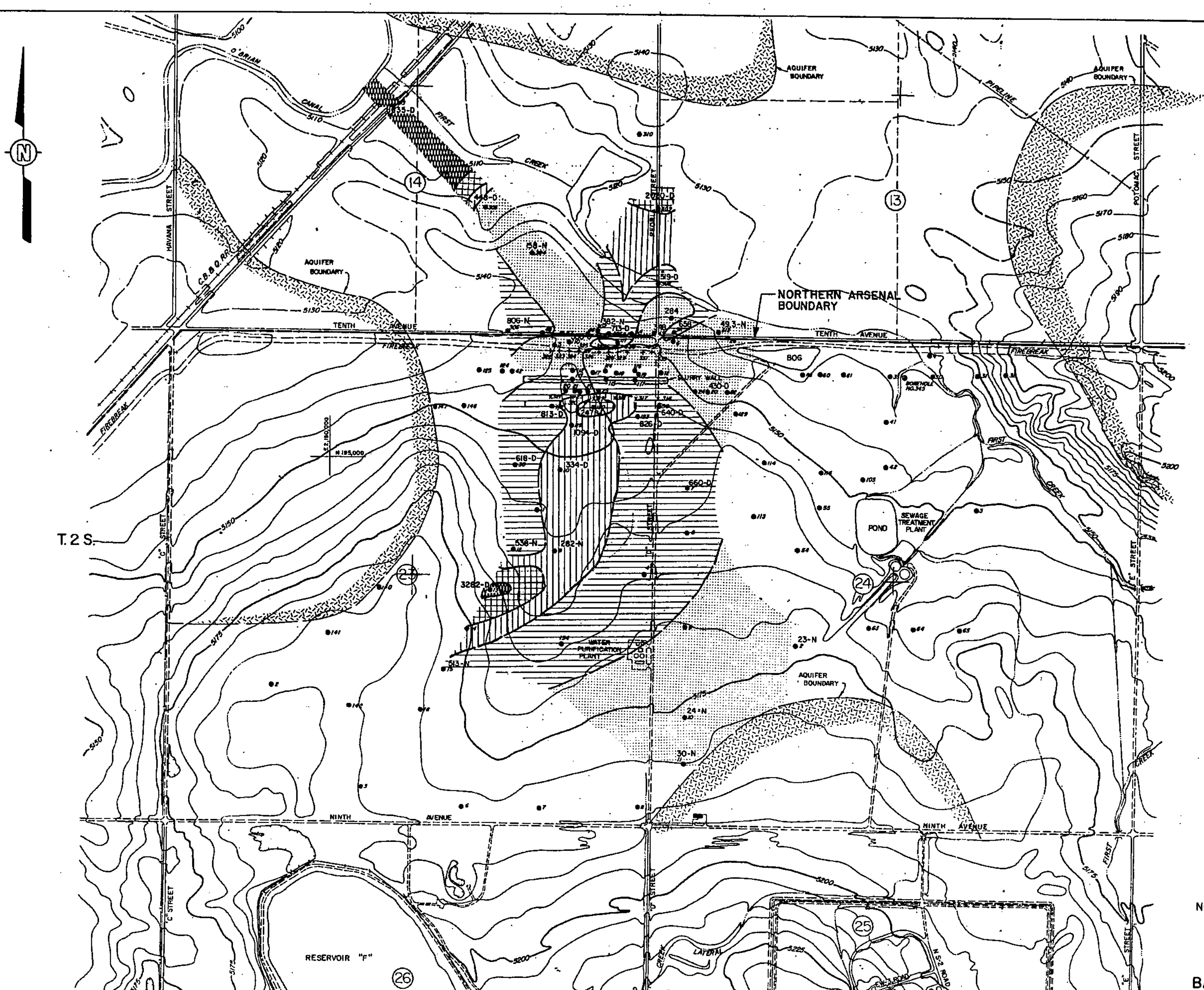
BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

007018-00 (7)

87900055 (7)

DRAWN BY	S.L.T. 6-30-79	CHECKED BY	[illegible] 7/6/79	APPROVED BY	JCM 7-25-79	DRAWING NUMBER	RM79-389-E3



LEGEND

DIMP CONCENTRATION IN MICROGRAMS/LITER

- 0-500
- 500-1000
- 1000-2000
- 2000-3000
- > 3000

49.3-N NOVEMBER DATA

813-D DECEMBER DATA

● MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)

+ RECHARGING WELL

× DEWATERING WELL

CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)

CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)

BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)

NOTE:
CONCENTRATION BANDS SHOWN ARE INTERPOLATIONS BETWEEN KNOWN POINTS AND MAY NOT BE REPRESENTATIVE OF ACTUAL CONDITIONS IN AREAS WITH SPARCE DATA.
OPEN AREAS INDICATE NO DATA.

SCALE

500 0 500 1000 FEET

FIGURE 17
DIMP CONCENTRATION MAP; NOVEMBER – DECEMBER, 1978

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

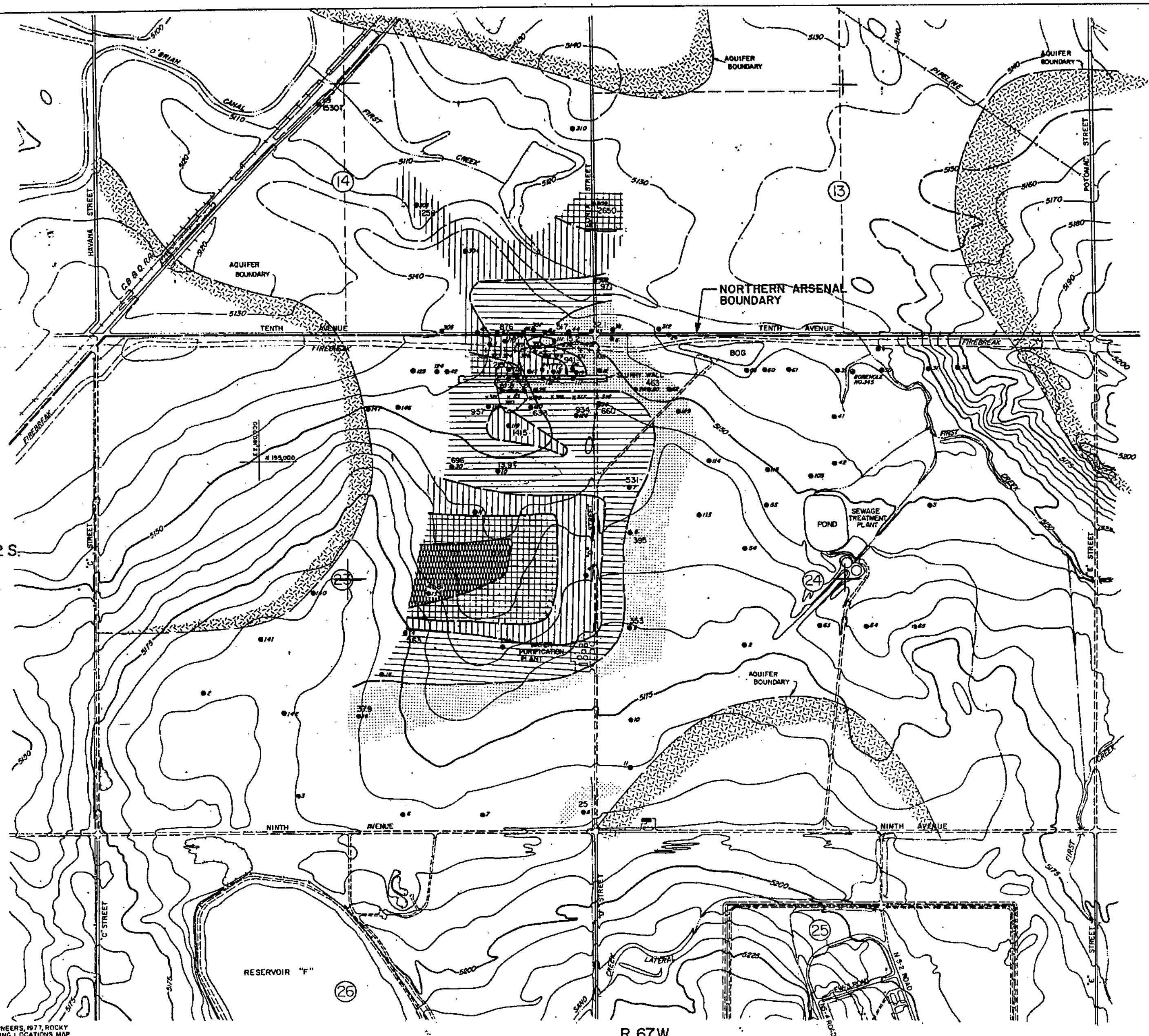
BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

007016-00 (8)

REFERENCE
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE: 1:24000

87900055 (6)



LEGEND

DIMP CONCENTRATION IN MICROGRAMS / LITER

- 0-500
- 500-1000
- 1000-2000
- 2000-3000
- > 3000
- MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)
- RECHARGING WELL
- DEWATERING WELL
- CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)
- CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)
- BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)
- ? QUESTIONABLE DATA NOT USED IN EVALUATION

NOTE: CONCENTRATION BANDS SHOWN ARE INTERPOLATIONS BETWEEN KNOWN POINTS. AND MAY NOT BE REPRESENTATIVE OF ACTUAL CONDITIONS IN AREAS WITH SPARCE DATA. OPEN AREAS INDICATE NO DATA.

SCALE
500 0 500 1000 FEET

FIGURE 18
DIMP CONCENTRATION MAP
MARCH, 1979

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

007016-00 (8)

DRAWN BY	S.L.T.	6-30-79	CHECKED BY	[illegible]	7/6/79	APPROVED BY	JCH	7.25.79	DRAWING NUMBER	RM79-389-E5

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE = 1:24000

B7800065 (8)

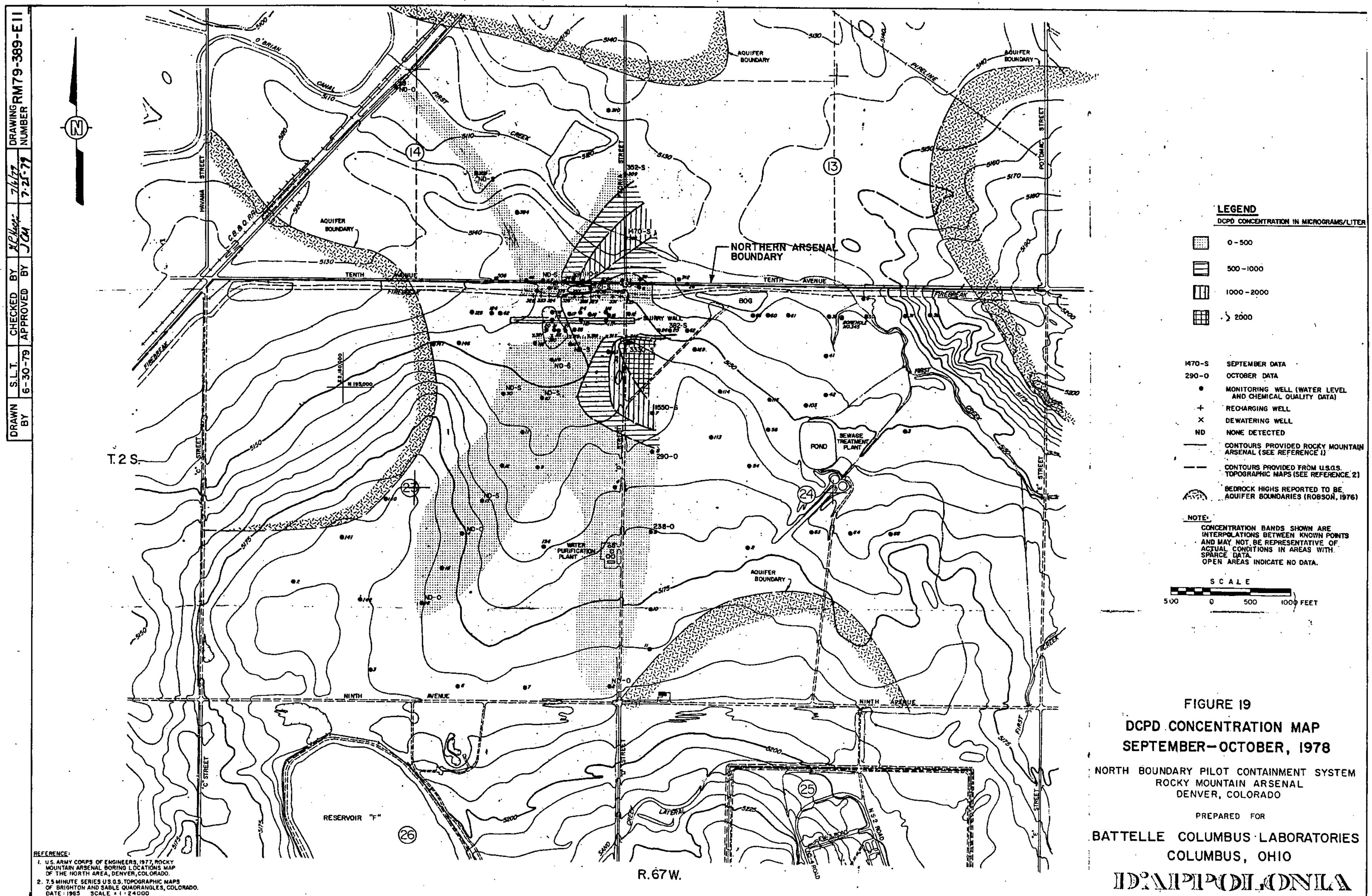


FIGURE 19

DCPD CONCENTRATION MAP
SEPTEMBER–OCTOBER, 1978

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

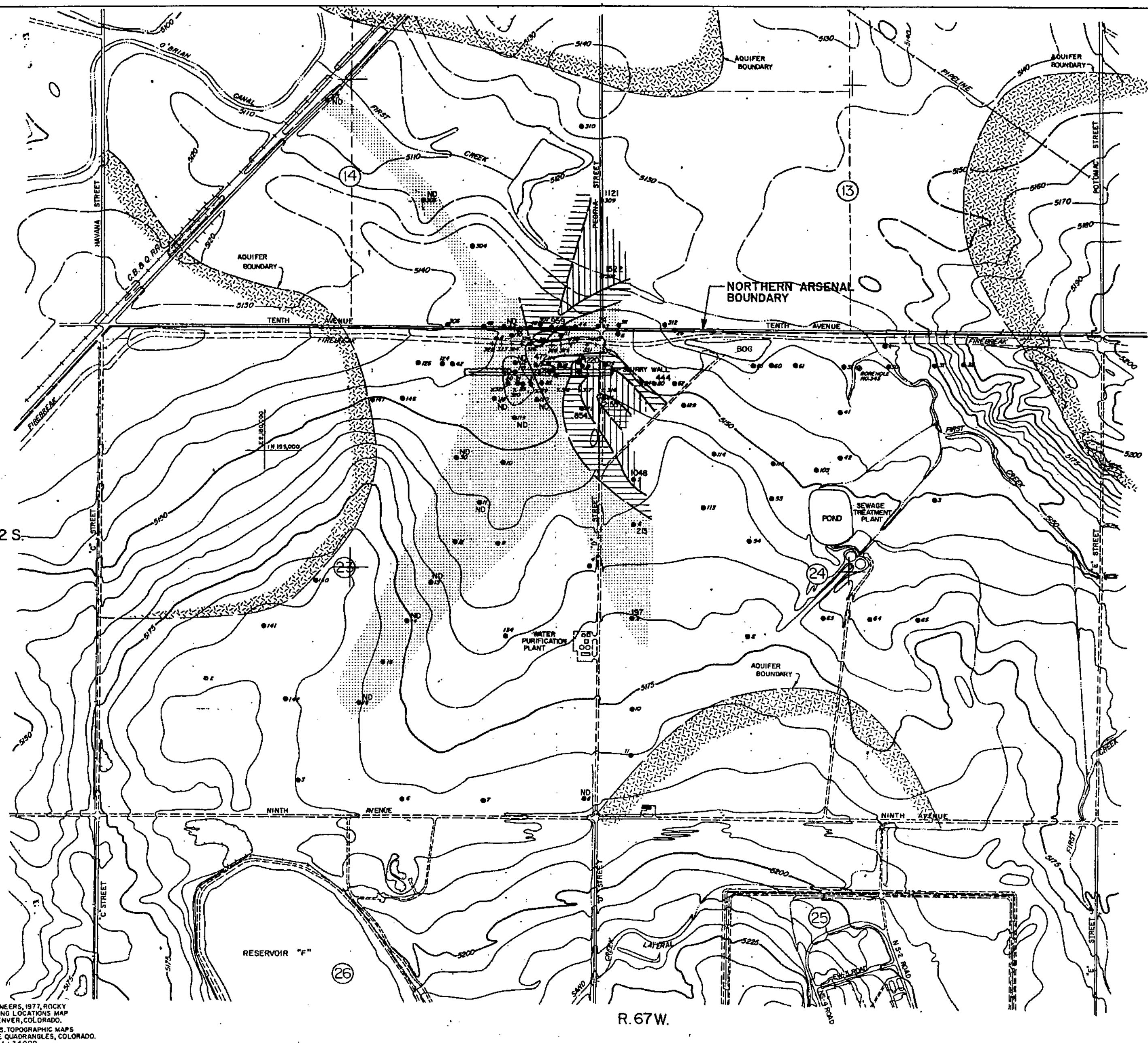
PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

87900065 (10) 007016-00 (10)

DRAWN BY	S.L.T.	CHECKED BY	[illegible]	2/6/79	DRAWING NUMBER	RM79-389-E9
	6-30-79	APPROVED BY	JCH	7-24-79		



LEGEND

DCPD CONCENTRATION IN MICROGRAMS/LITER

- 0-500
- 500-1000
- 1000-2000
- > 2000
- ● MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)
- + RECHARGING WELL
- × DEWATERING WELL
- ND NONE DETECTED
- CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)
- CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)
- BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)

NOTE: CONCENTRATION BANDS SHOWN ARE INTERPOLATIONS BETWEEN KNOWN POINTS AND MAY NOT BE REPRESENTATIVE OF ACTUAL CONDITIONS IN AREAS WITH SPARCE DATA. OPEN AREAS INDICATE NO DATA.

SCALE

500 0 500 1000 FEET

FIGURE 20
DCPD CONCENTRATION MAP
MARCH, 1979

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

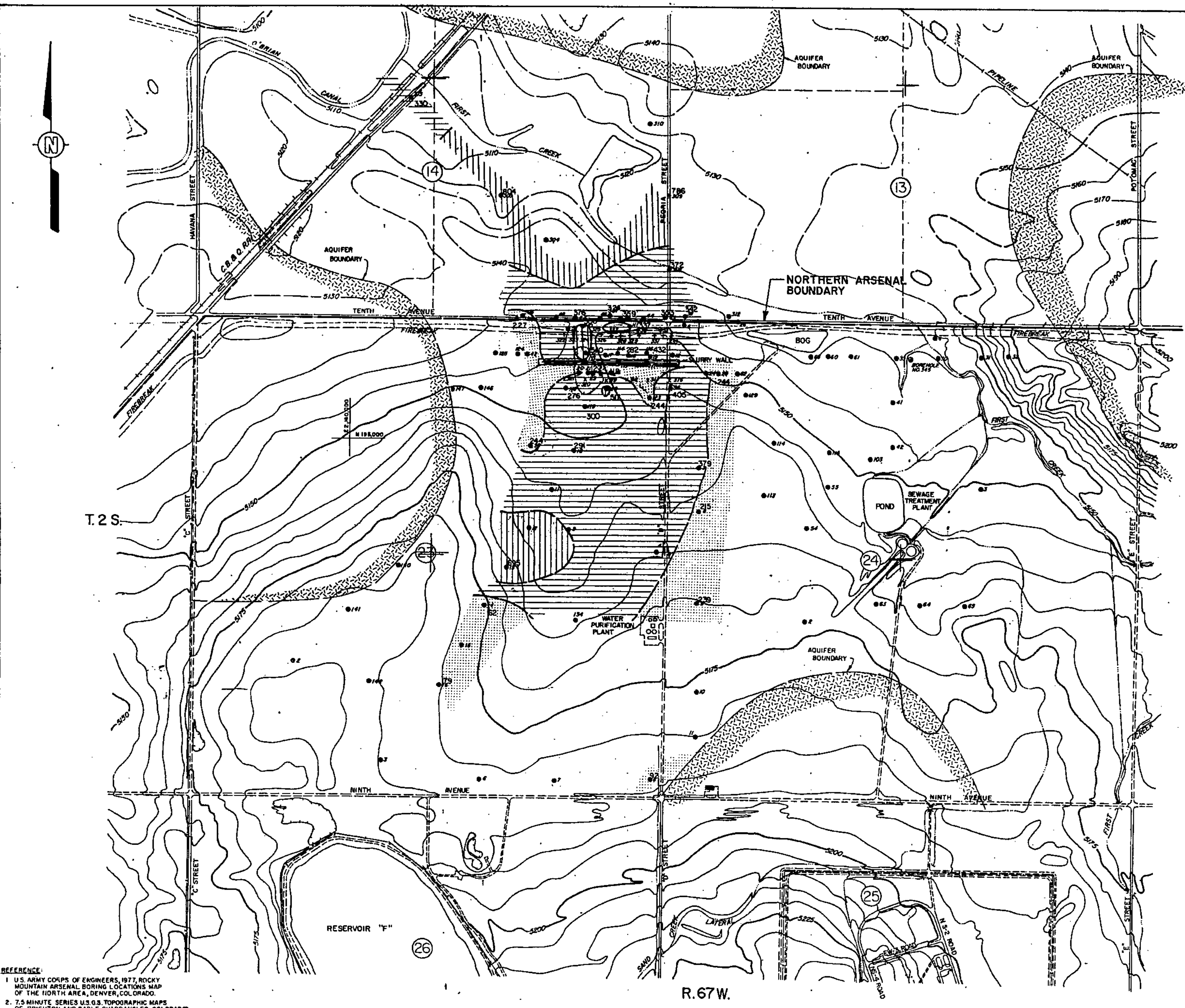
D'APPOLONIA

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE = 1:24000

007016-00 (11)

87900065 (11)

DRAWN BY	S.L.T. 6-30-79	CHECKED BY / APPROVED BY	J.K.Heaps 7/6/79 / JCH 7/25/79	DRAWING NUMBER	RM79-389-E8



LEGEND

CHLORIDE CONCENTRATION IN MILLIGRAMS/LITER

- 0-250
- 250-500
- > 500

- ● MONITORING WELL (WATER LEVEL AND CHEMICAL QUALITY DATA)
- \+ RECHARGING WELL
- × DEWATERING WELL
- —— CONTOURS PROVIDED ROCKY MOUNTAIN ARSENAL (SEE REFERENCE 1)
- — — CONTOURS PROVIDED FROM U.S.G.S. TOPOGRAPHIC MAPS (SEE REFERENCE 2)
- BEDROCK HIGHS REPORTED TO BE AQUIFER BOUNDARIES (ROBSON, 1976)

NOTE: CONCENTRATION BANDS SHOWN ARE INTERPOLATIONS BETWEEN KNOWN POINTS, AND MAY NOT BE REPRESENTATIVE OF ACTUAL CONDITIONS IN AREAS WITH SPARCE DATA. OPEN AREAS INDICATE NO DATA.

SCALE
500 0 500 1000 FEET

FIGURE 21
CHLORIDE CONCENTRATION MAP
MARCH, 1979

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

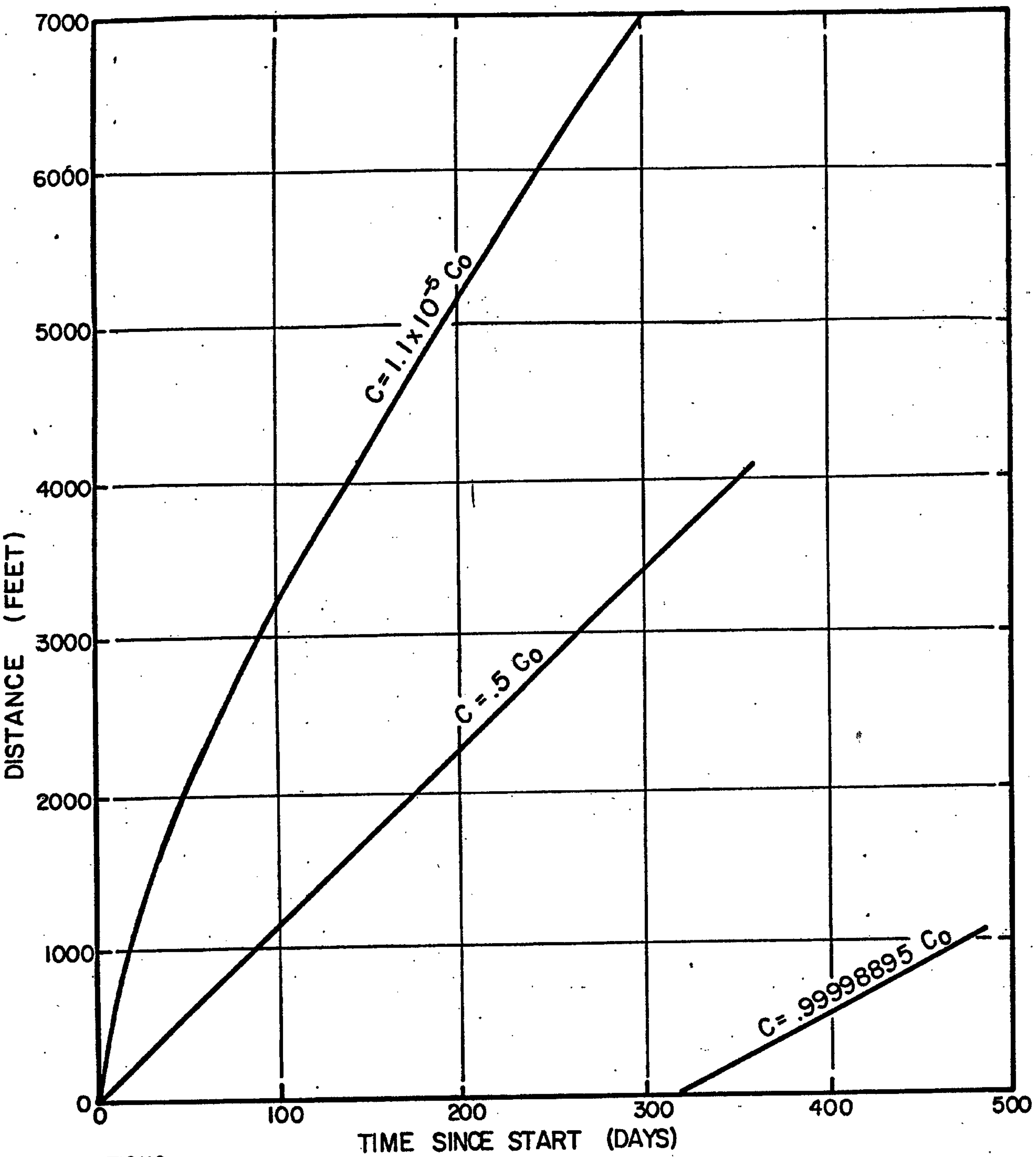
D'APPOLONIA

REFERENCE:
1. U.S. ARMY CORPS OF ENGINEERS, 1977, ROCKY MOUNTAIN ARSENAL BORING LOCATIONS MAP OF THE NORTH AREA, DENVER, COLORADO.
2. 7.5 MINUTE SERIES U.S.G.S. TOPOGRAPHIC MAPS OF BRIGHTON AND SABLE QUADRANGLES, COLORADO. DATE: 1965 SCALE = 1:24000

007016-00 (12)

87900055 (12)

DRAWN BY S.L.T. 7-5-79 | CHECKED BY G.R.H. 7-25-79 | APPROVED BY JCM 7-25-79 | DRAWING NUMBER 79-389-1



ASSUMPTIONS:

PERMEABILITY : 400 FT/DAY

EFFECTIVE POROSITY : 30%

GRADIENT : 0.0086

DISPERSION COEFFICIENT : 1150 FT^2/DAY

EQUATION USED : $\frac{c}{c_0} = \frac{1}{2}\,\mathrm{erfc}\,\frac{(x-V_x t)}{2(D_L t)^{1/2}}$ (BOUWER, 1978)

WHERE:

- c = CONCENTRATION AT POINT
- c_0 = ORIGINAL CONCENTRATION
- V_x = ACTUAL FLOW VELOCITY
- D_L = DISPERSION COEFFICIENT
- t = TIME SINCE MOVEMENT BEGAN
- X = DISTANCE FROM ORIGIN
- erfc = COMPLEMENTARY ERROR FUNCTION

FIGURE 22

THEORETICAL
EFFLUENT TIME-DISTANCE GRAPHS

NORTH BOUNDARY PILOT CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA